Asteroids

Floating Flotsam in the Solar System

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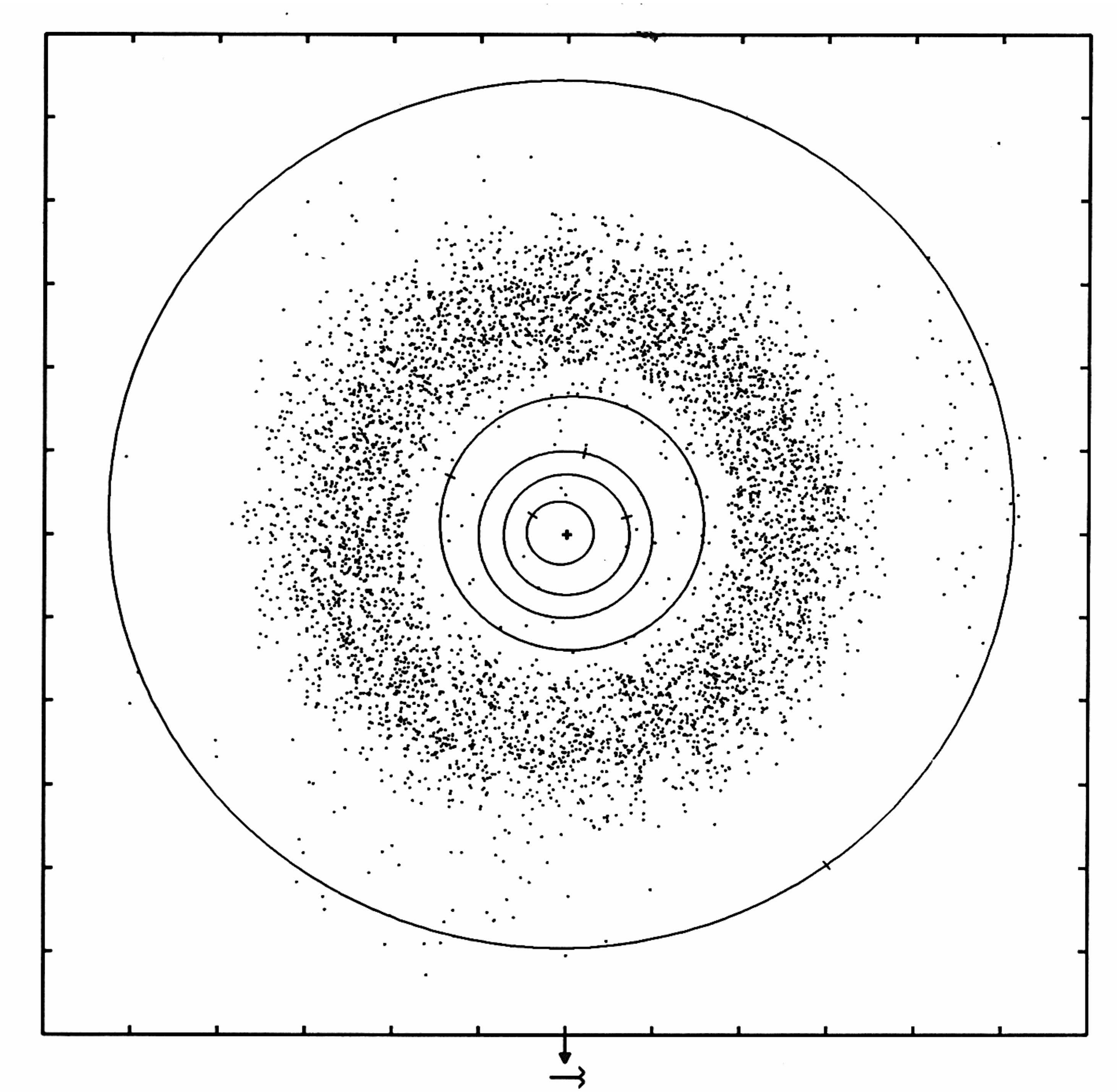
Asteroids

- Where are they?
- What are they?
- What do they look like?
- Spin
- How did they get to where they are?
- Where are they going?
- Why study asteroids?
- Fun Stuff
  - How we determine asteroid masses
  - Chaotic motion in the asteroid belt

Where are they?

- Main belt spans 4:1 resonance to 2:1 resonance
- "Near Earth" asteroids (NEAs)
- Trojans (1:1 resonance)
- Distant objects
  - Kuiper belt (short-period comet reservoir)
  - none between Jupiter and Saturn
  - "true" asteroids stop at the Trojans

An Asteroids Snapshot



The Asteroid Distribution

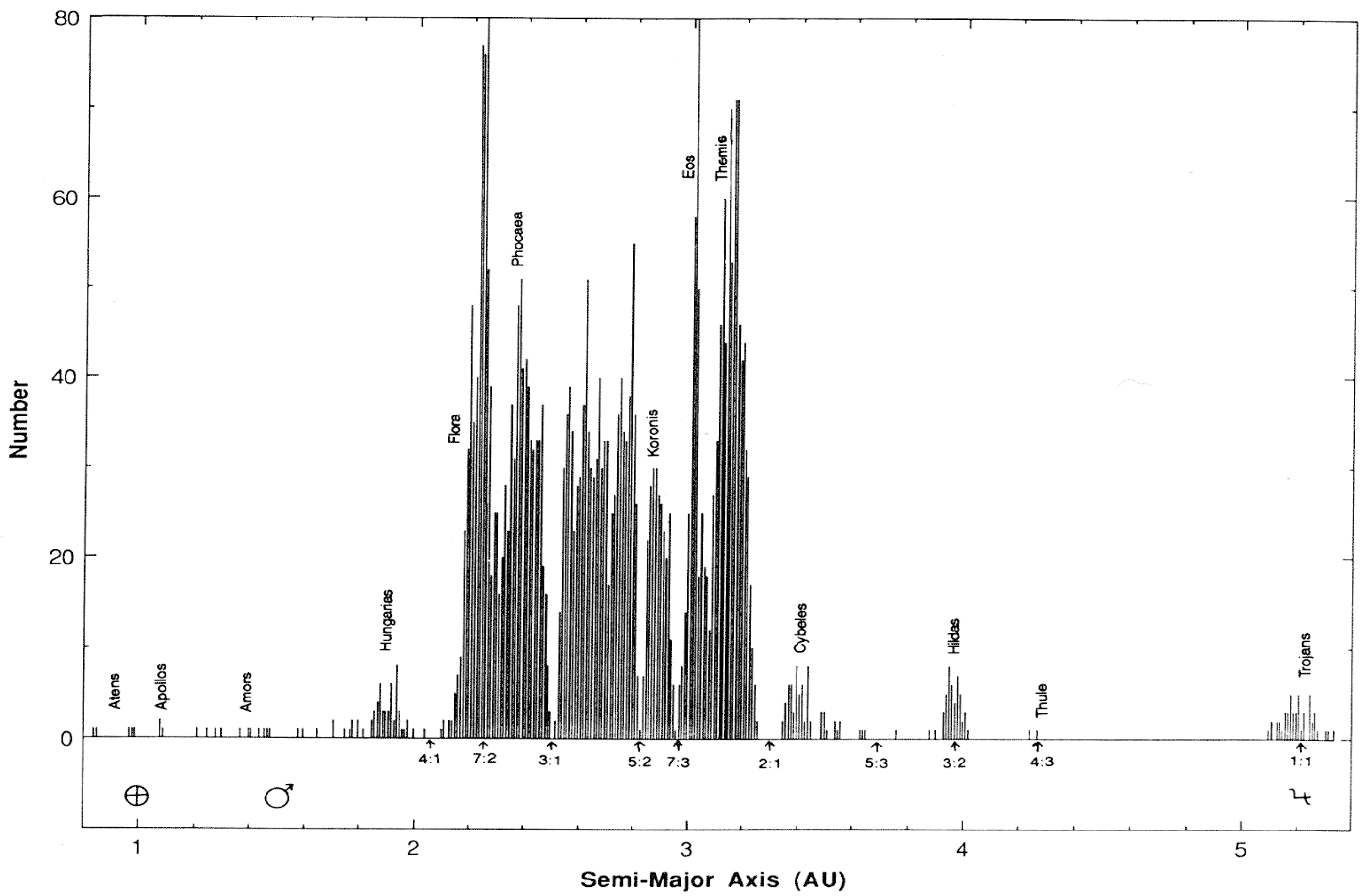
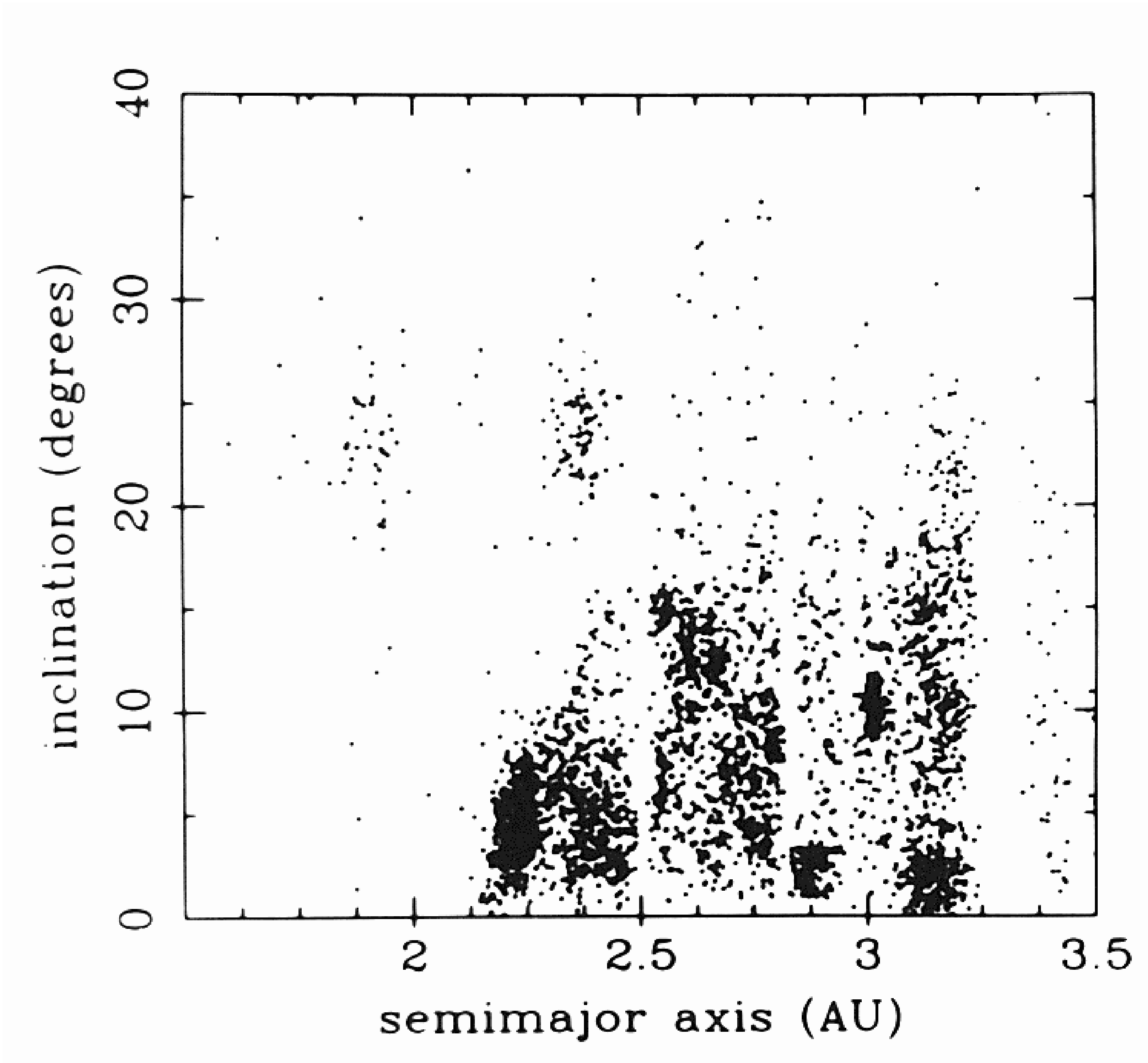


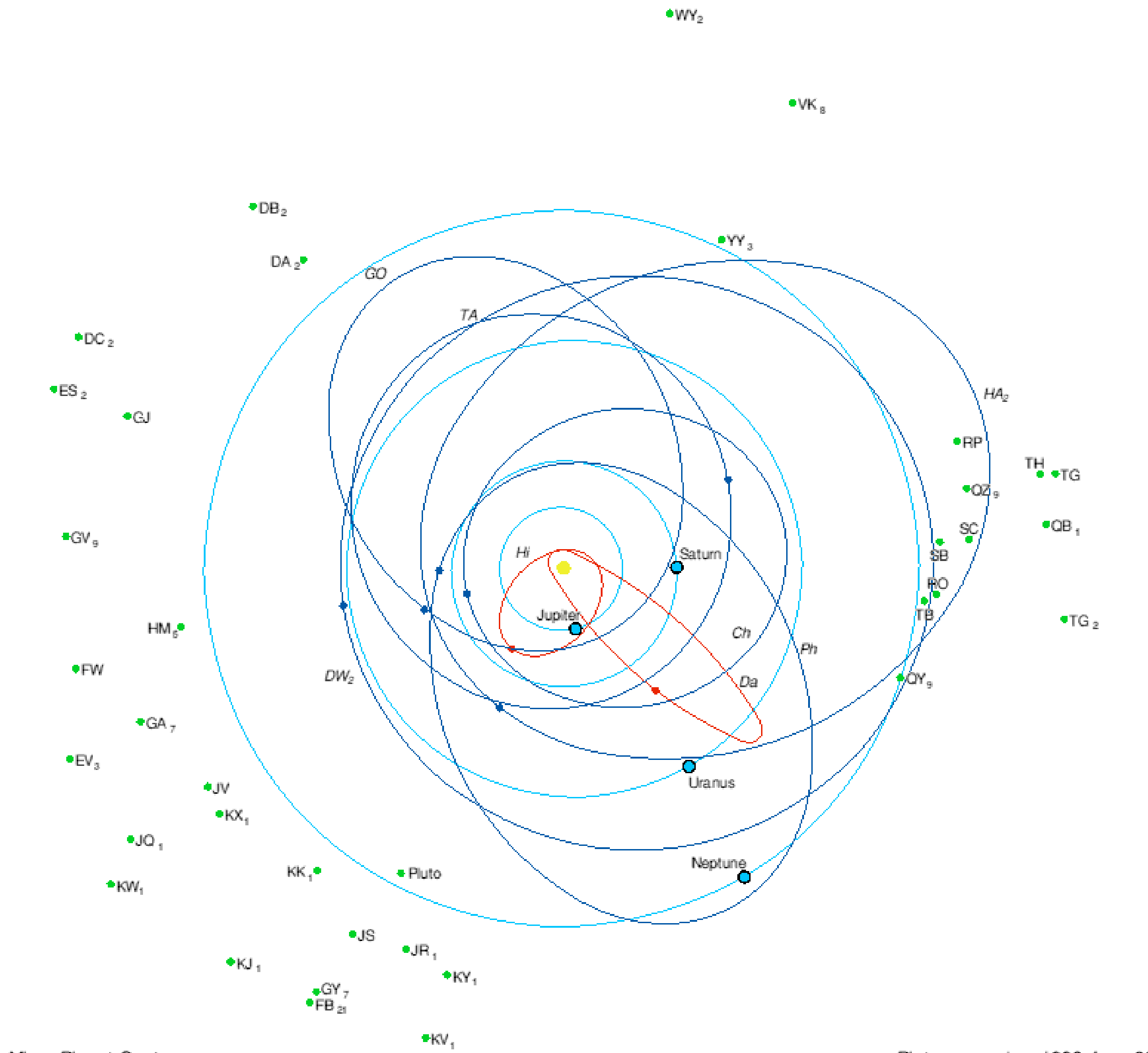
Fig. 2. Heliocentric distribution of orbital semimajor axes for nearly 4000 numbered asteroids. Commonly referred to regions and the major Jovian resonances are labeled. Other frequently referred to zones (such as those defined by Zellner et al. 1985*a*) and their eccentricity and inclination boundaries are listed in Table I of the chapter by Gradie et al. Compare this diagram with that on the back cover (which depicts the actual asteroid positions at a given moment in time) to see how orbital eccentricities tend to "smear" this distribution.

- Kirkwood gaps

The Asteroid Distribution



The Outer Solar System



What are they?

- Approaching 10,000 numbered objects
- Size
  - from occultations (~50)
    - 933 km (Ceres) down to <10 (observational limits)
  - from infrared observations
    - dependent on accuracy of thermal models
  - IRAS:
    - over 1800 known objects recognized
    - ~10000 asteroids detected
- Mass
  - direct measurements for a few (later in talk)
  - from diameters and the adoption of "reasonable" densities
- Composition
  - spectroscopy
  - meteorites

IRAS Diameters

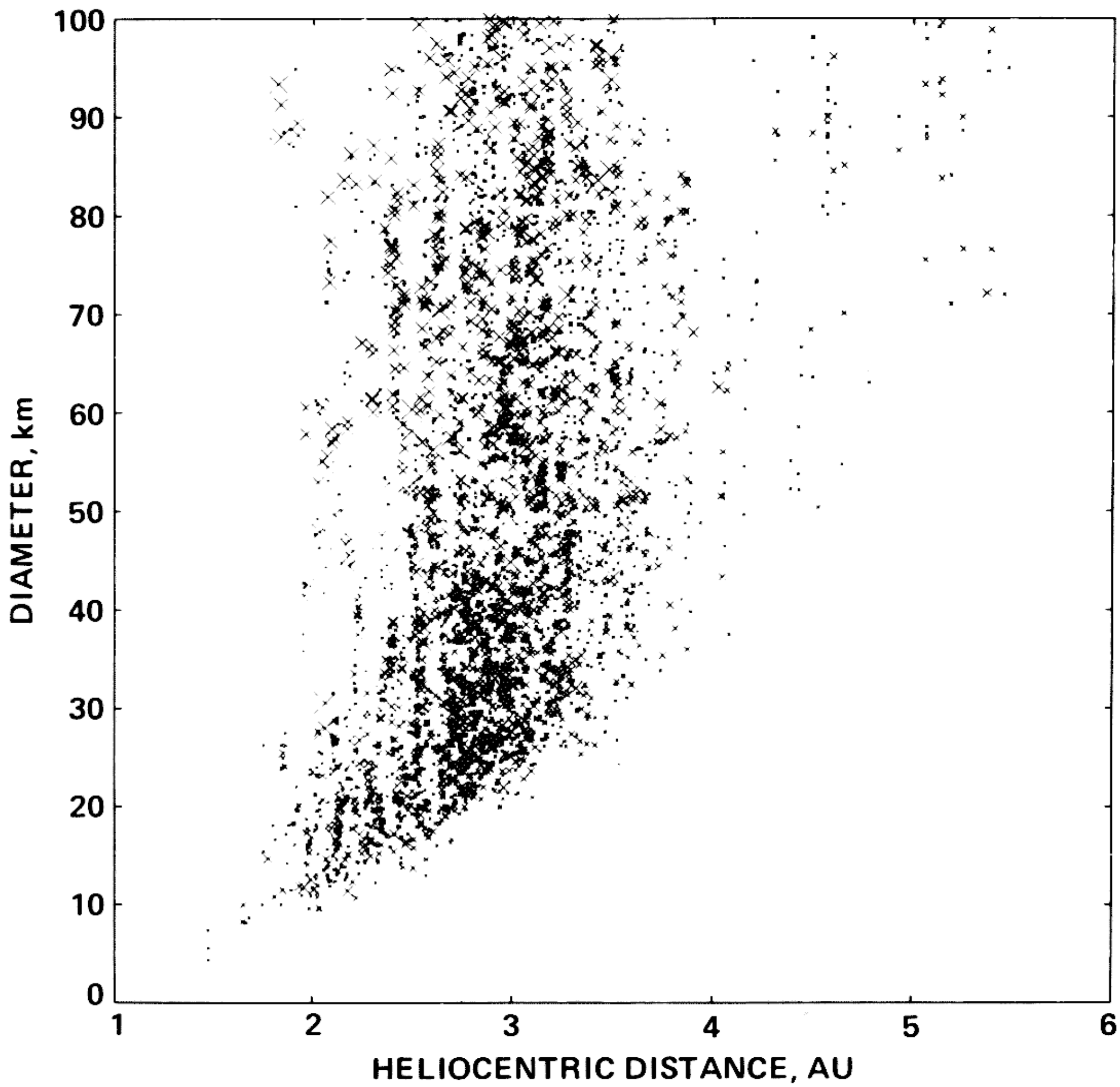
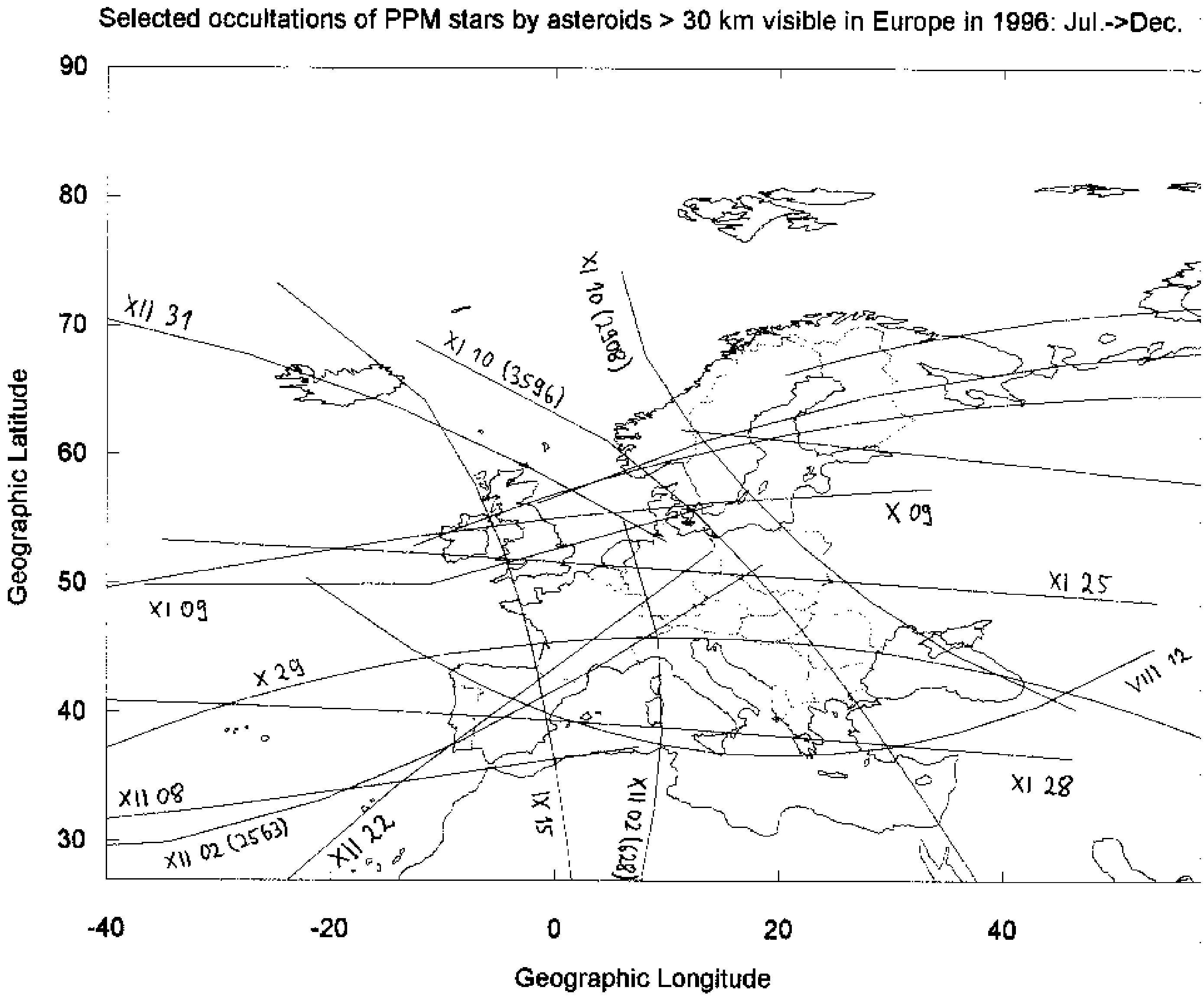


Fig. 3. Diameter plotted against heliocentric distance for IRAS asteroids with low visual geometric albedos ($p_V < 0.1$). Separate model diameters have been derived from the observed flux density at 25 μm for each accepted observation.

What do they look like?

- Shape
  - from stellar occultations (a handful)
  - speckle interferometry
  - radar
- Appearance
  - speckle interferometry
    - short exposures (10-50 ms)
    - narrow bandpass (100-300 A)
    - combine in Fourier domain to recover *diffraction limited* information
    - image reconstruction
    - resolved, very bright objects only

Occultation Paths



Shape from Profile Occultations

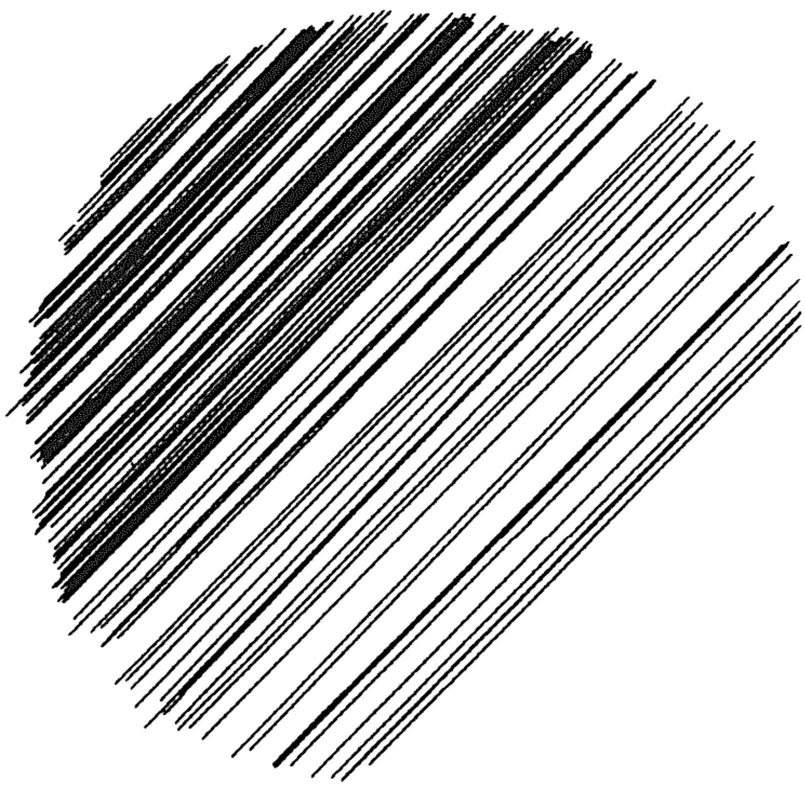


Fig. 1. Chords across 2 Pallas derived from observations of the 29 May 1983 occultation of 1 Vulpeculae (D. W. Dunham et al. 1983).

Speckle Interferometry Image of Vesta

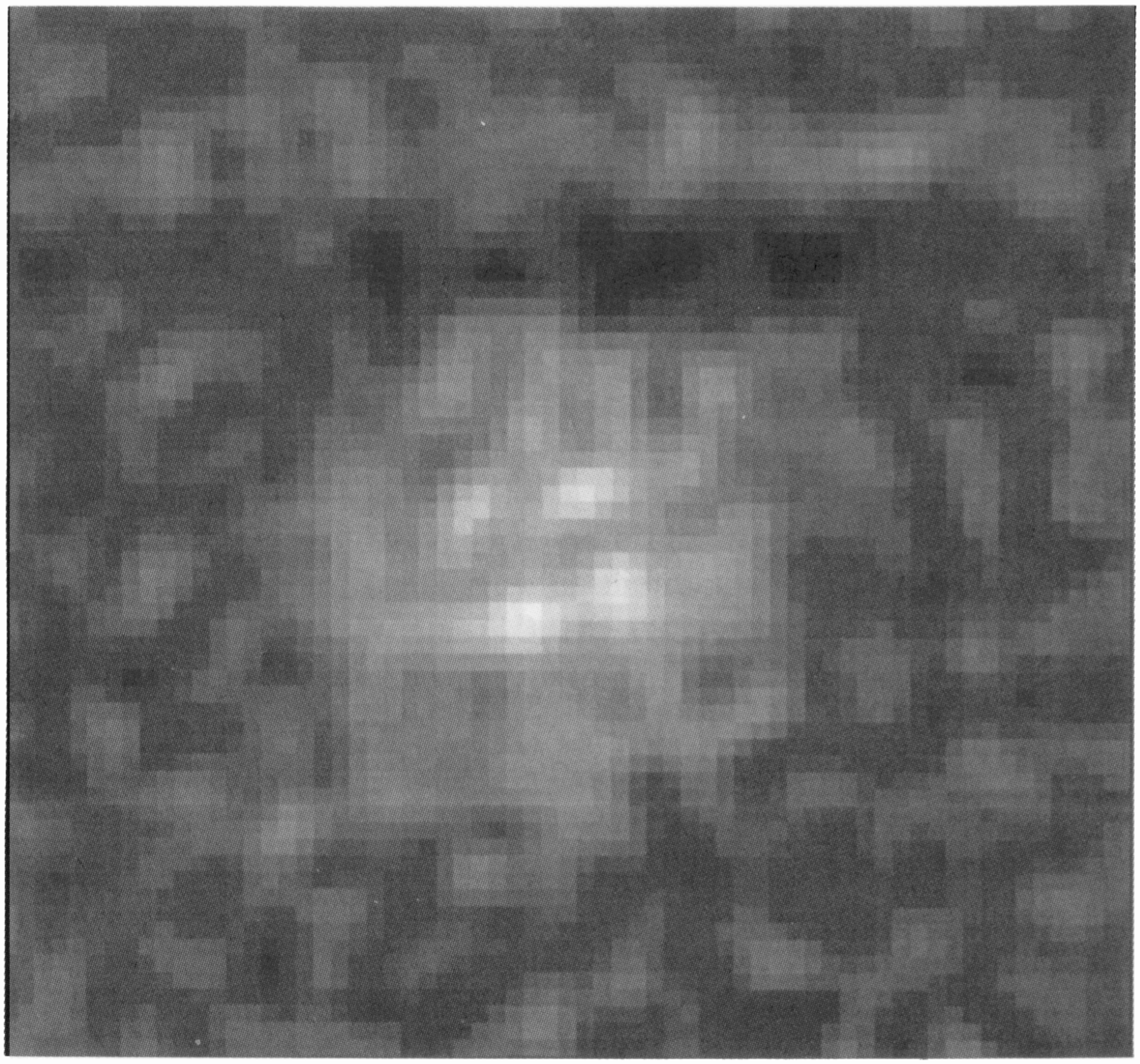


Fig. 4. Reconstructed image of 4 Vesta. This reconstruction of an image was made with the Knox-Thompson algorithm applied to the first Vesta observation of 14 Nov. 1986. The size of Vesta at this time was 0.50 by 0.47 arcsec with the position angle of the long axis oriented 50° West (counterclockwise) of North (left) as determined from PSSA.

What do they look like?

- Appearance
  - radar doppler/delay images
    - Arecibo and Goldstone: (Steven Ostro's toys)
  - Galileo!
- Surface texture
  - polarimetry

Polarization

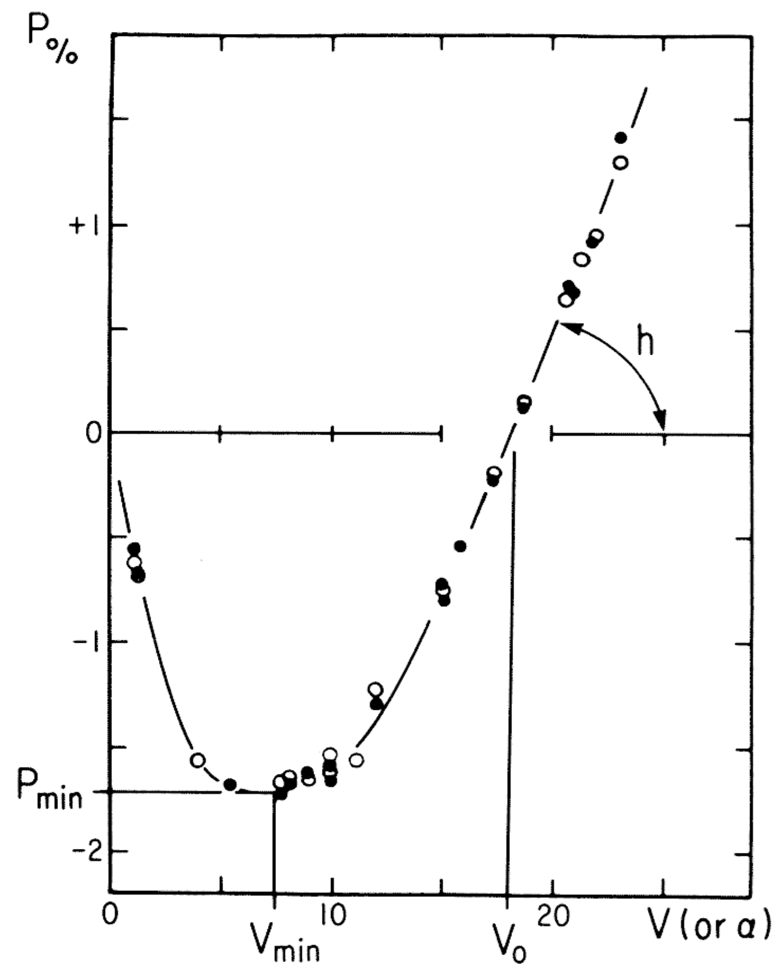


Fig. 1. Curve of polarization showing degree of linear polarization as a function of solar phase angle, for asteroid 1 Ceres. Definitions are shown for the polarization parameters P_{min}, V_0 and h (figure adapted from Zellner et al. 1974).

Polarization

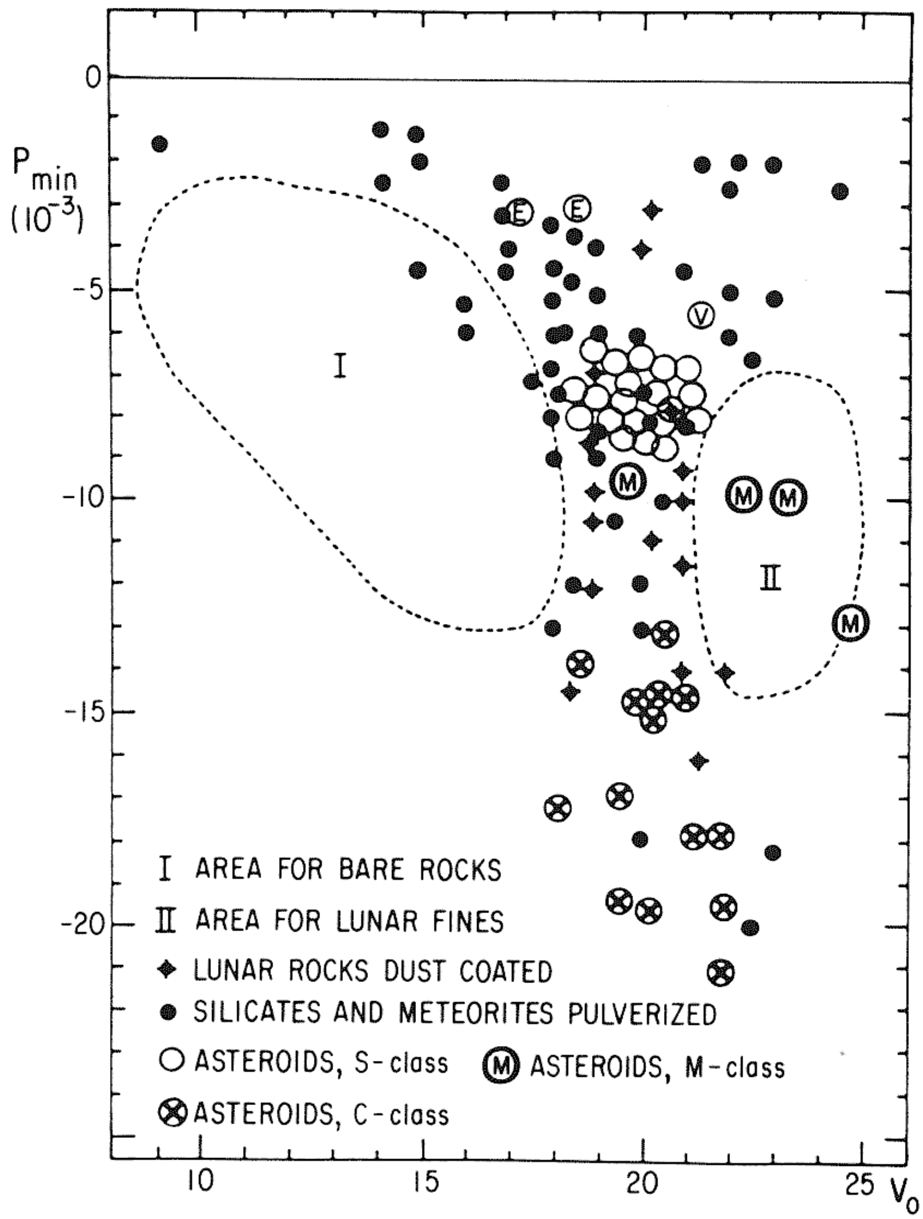
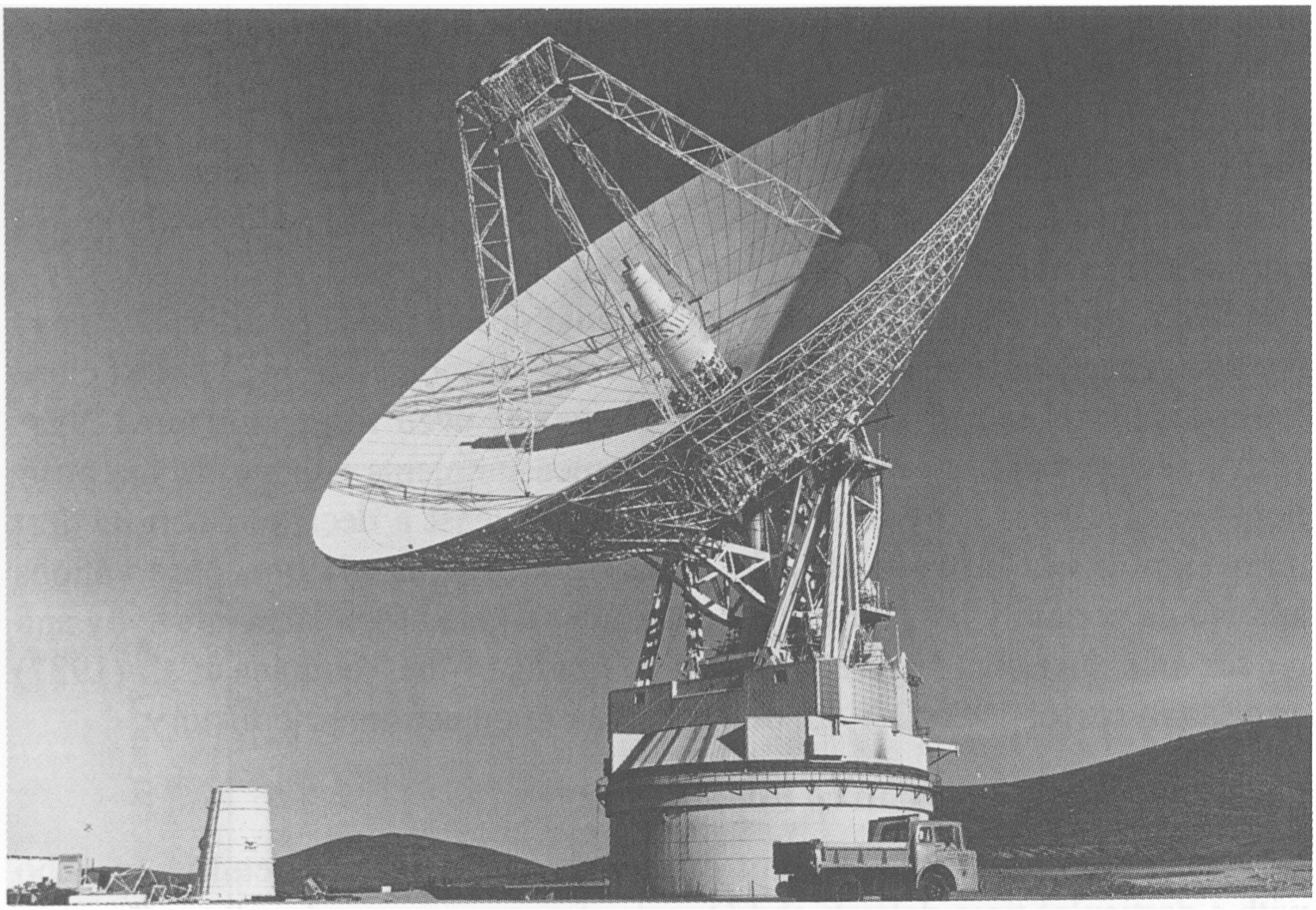
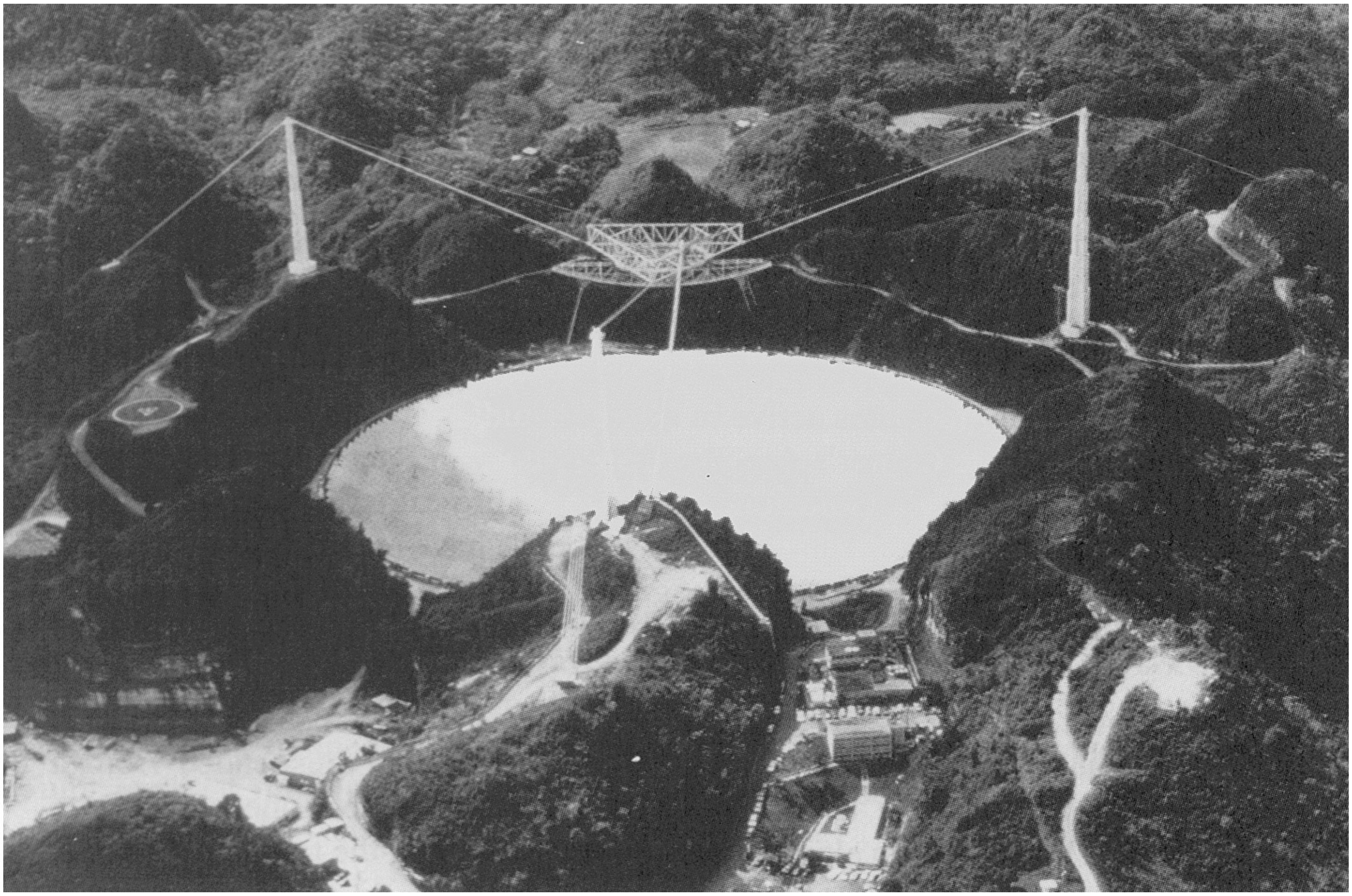


Fig. 5. Polarization of asteroids in the P_{min}–V_0 diagram of Fig. 3. Asteroids are in the zone between the area I, corresponding to large rock fragments and area II for fine powders such as lunar samples. Both S (circles), E and V asteroids and C asteroids (crossed circles) appear to be covered with a coarse-grained regolith (figure from Dollfus et al. 1977). M asteroids occupy area II (Dollfus et al. 1979).

Goldstone

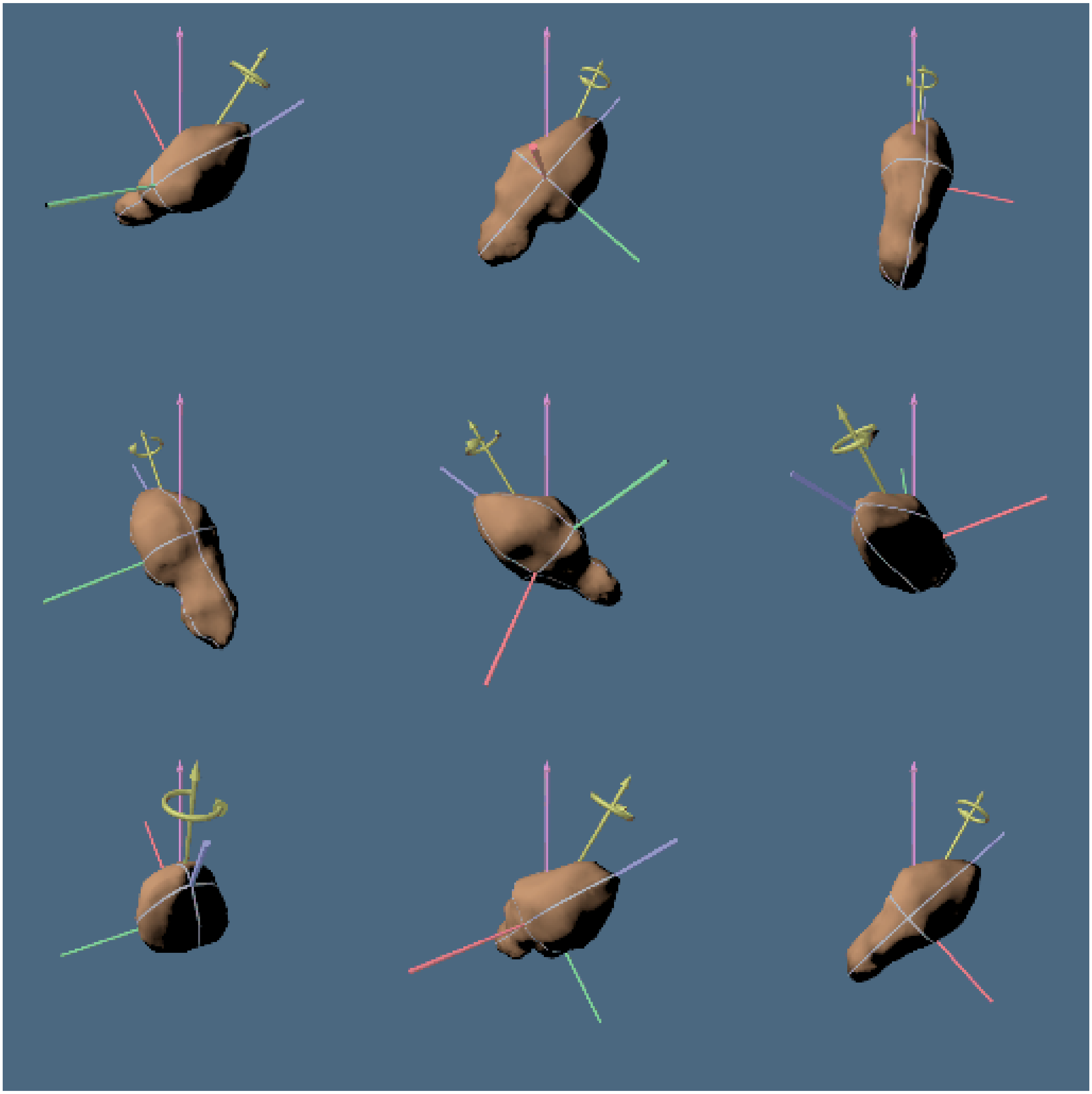


Arecibo



1620 Geographos (radar image)

4179 Toutatis (radar image)



Ida and Dactyl (Galileo visual image)

Do they spin or just sit there?

- They spin
- How spin & orientation are measured
  - photometry
  - radar
- Photometry:
  - spin periods
  - spin orientations
  - ellipsoidal shape parameters
    - from amplitudes and absolute magnitudes
- Places constraints on collisional evolution of orbits around the Sun

An Asteroid Light Curve

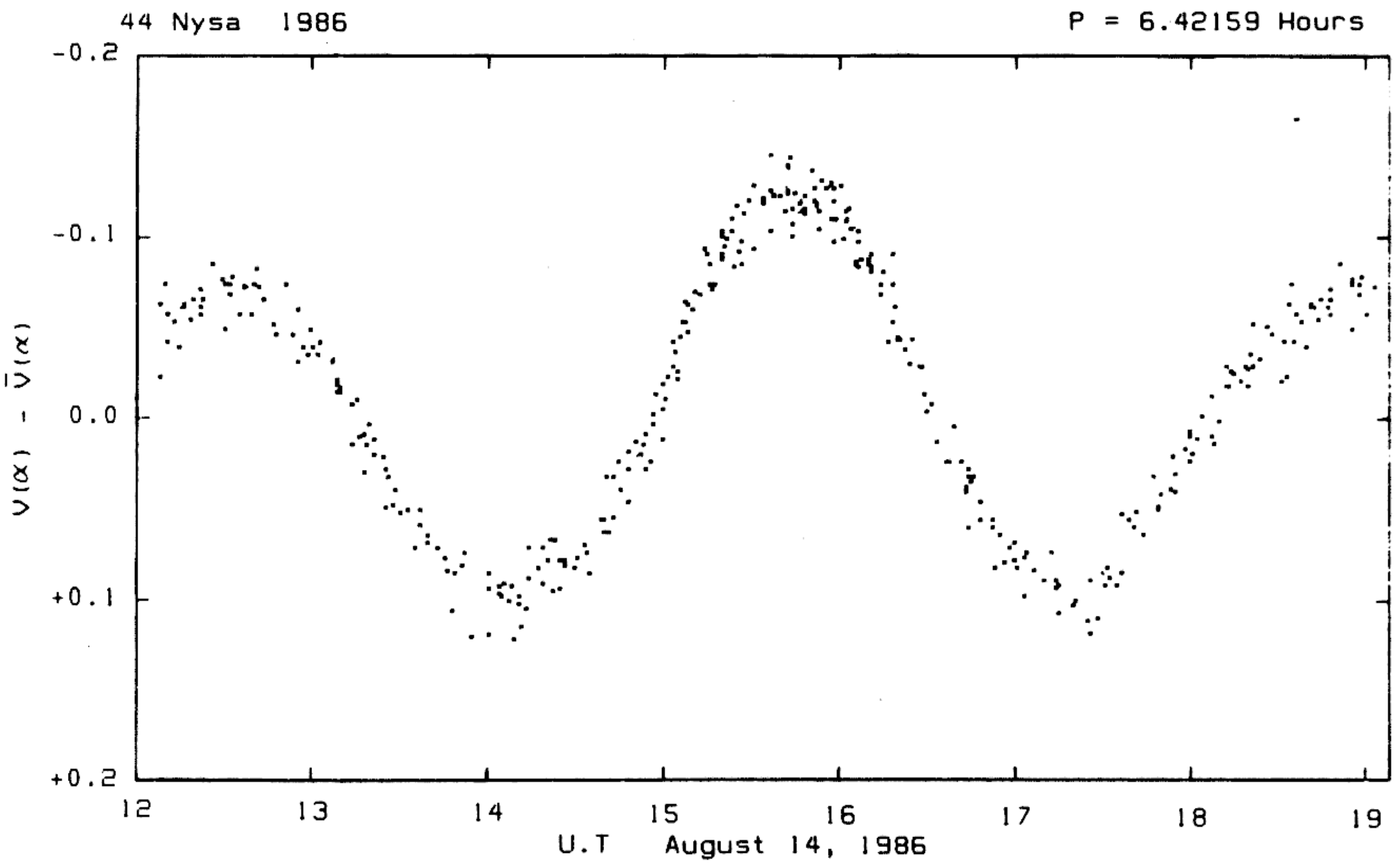


Fig. 2. The composite lightcurve of 44 Nysa, obtained on 23 nights from June to October, 1986. There are 340 individual observations in this plot. The lightcurve was constructed with the Fourier-analysis method described in the text. There was some slight change in lightcurve form over the course of the observations, as revealed by the strings of deviant points near the extrema at 14^h and $15\overset{h}{.}5$.

Another Asteroid Light Curve

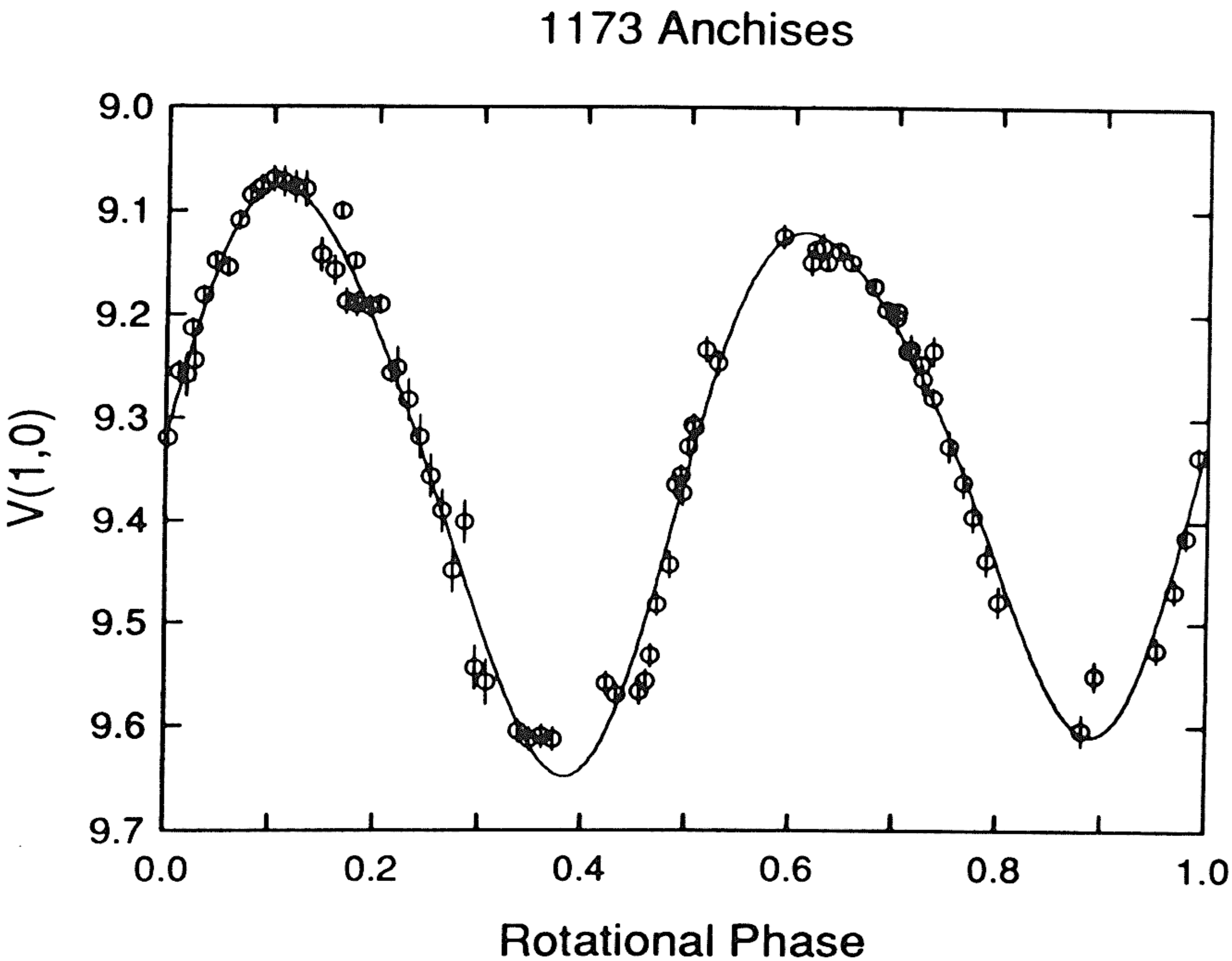


Fig. 2. Lightcurve of Trojan asteroid 1173 Anchises, corrected for distance and solar phase-angle effects. Observations were made with the Cerro Tololo 0.9-m telescope and a GEC CCD detector. The smooth curve is a four-component Fourier series used to remove the effects of the mean lightcurve in modeling the phase properties (figure from French 1987).

Pole Latitudes from Photometry

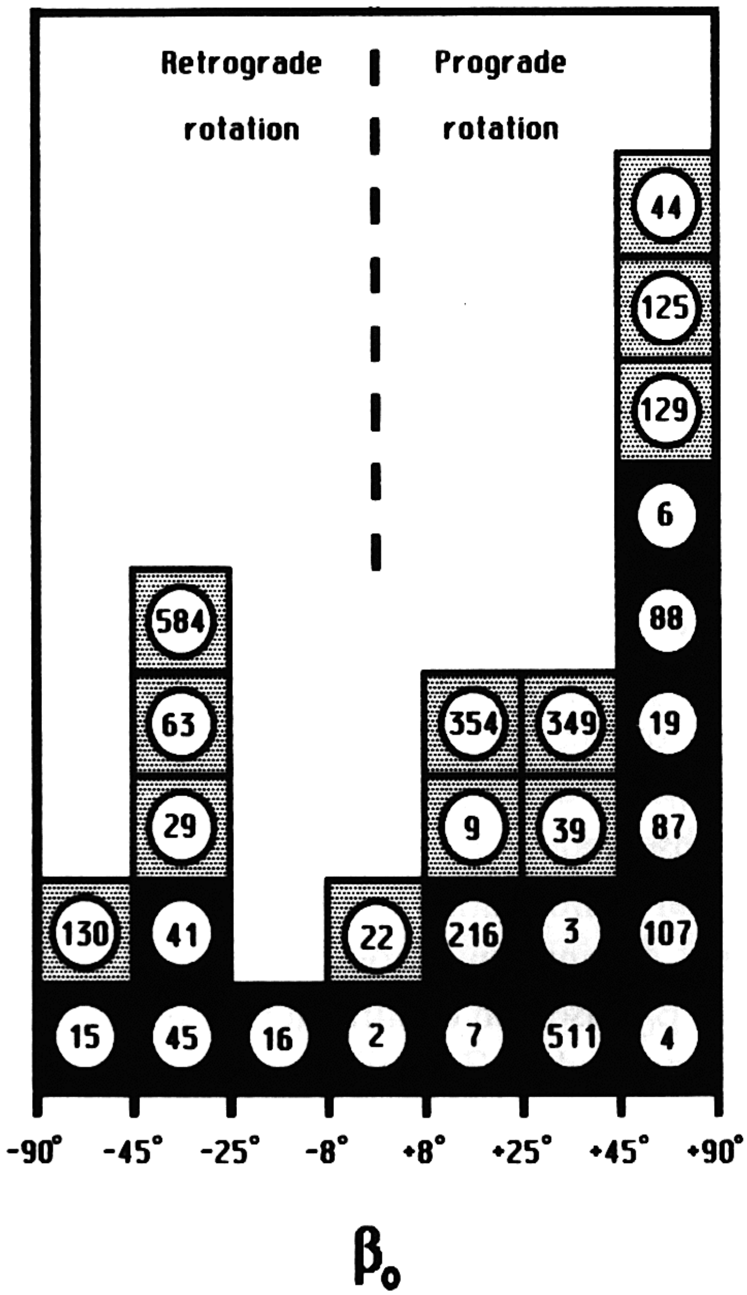


Fig. 11. Distribution of pole latitudes for a set of large main-belt asteroids. Black boxes indicate objects larger than 200 km and gray boxes, smaller objects. See also an alternative representation, where the distribution of the spin-vector components perpendicular to the ecliptic plane is given by Magnusson (1988).

Ellipsoidal Parameters from Photometry

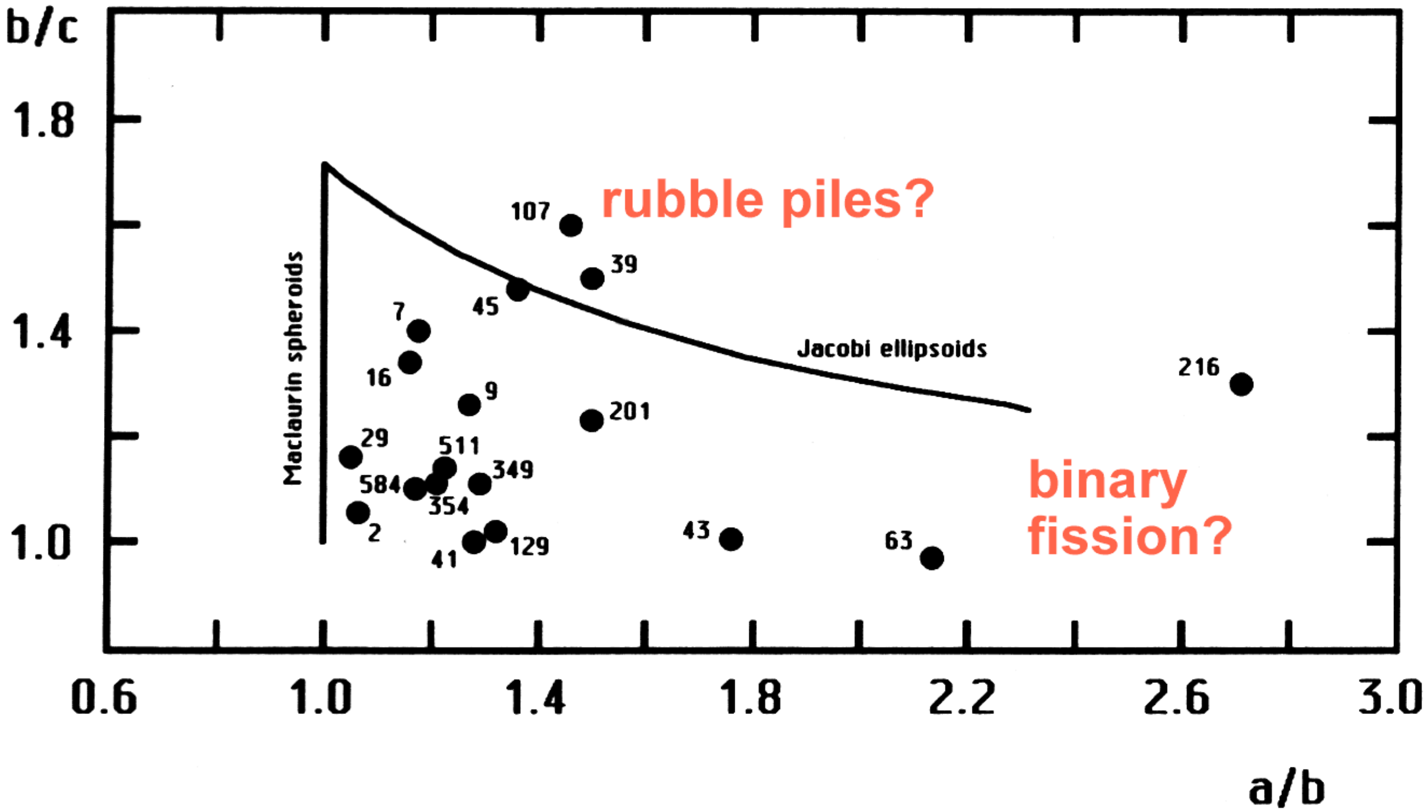


Fig. 10. A homogeneous set of ellipsoidal model parameters (a/b, b/c) for large main-belt asteroids. The loci of Maclaurin spheroids and Jacobi ellipsoids are also shown for comparison (Chandrasekhar 1969). Because of known observational biases, the number of asteroids near the Maclaurin spheroid curve is probably underestimated. Geometric scattering was assumed in the shape determination.

How did they get there?

- Titius-Bode law: a planet should be there
- Busted planet?
  - Solar system news (early formation edition): huge collision shatters planet!
  - probably not
- Failed planet
  - Perturbations from Jupiter kept a planet from fully forming in that region
    - Jupiter formed first
    - sets bounds on the timescale for growth of Jupiter and the rest of the gas giants (a Very Important Problem)
  - currently the most-favored theory
- Significant collisional evolution

Where are they going?

- Collisional evolution
  - can result in planet-crossing trajectories
  - smaller pieces: nongravitational effects
    - (early) inward spiraling from gas drag
    - (early) entrainment during outflow of nebular gas
    - Poynting-Robertson drag (dust)
- Dynamical evolution
  - removal from mean motion resonance regions
    - Kirkwood gaps
    - high-eccentricity particles collide with other main-belt particles
  - dynamical mechanism: chaos
    - Jack Wisdom's work in the early to mid 80s

The Short-Period Comet Invasion

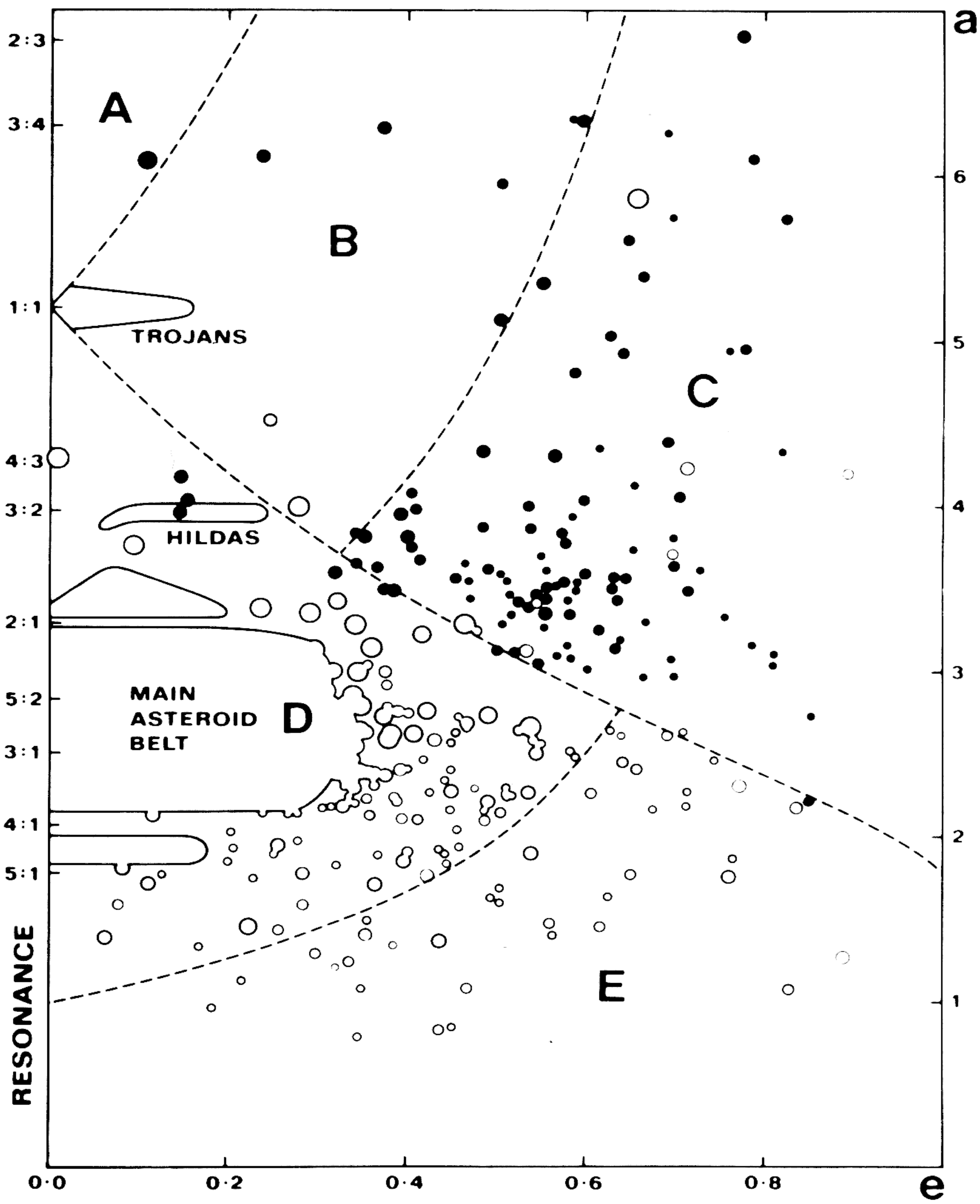


Fig. 1. Short-period comets (solid circles) and asteroids (open circles) plotted on a scatter diagram of semimajor axis vs eccentricity (Kresák 1985). Increasing circle size indicates estimated size of the objects: diameter < 1 km or lost, 1 to 3 km, 3 to 10 km, 10 to 30 km and > 30 km. Different regions identified within the diagram are: (A) transjovian region, (B) Jupiter domain of weak cometary activity, (C) Jupiter domain of strong cometary activity, (D) minor planets region, and (E) Apollo-Aten region. The dashed line going from upper left to lower right corresponds to a Tisserand invariant of 3.0, the usual dividing line between comets and asteroids. However, note the several asteroids above the line in the cometary region C; the figure has been modified to include seven new asteroids in or near region C discovered since Kresák's (1985) work was published.

Why study asteroids?

- Only existing planetesimals that date back to formation of solar system
  - provide a snapshot of conditions that prevailed in the early stages of the solar system and planetary formation
  - places bounds on solar system formation theories
- Located in the transition region between inner (rocky) and outer (gas giants) planets
  - constraints on solar nebula parameters and evolution
  - constraints on planet formation processes
- Believe it or not, they noticeably affect the motions of the planets

Why study asteroids?

- Source for most meteorites
  - Dynamical evolution leads to planet-crossers
  - "Meteorites" includes the big ones, too
    - previous mass species extinctions
    - potential future mass extinctions!
  - distribution of meteorites spans several early stages of solar system formation
    - time scales for various processes
    - chemical composition
      - temperatures
      - pressures
      - characteristics of early Sun
      - characteristics of solar nebula

Why study asteroids?

- Laboratory for Hamiltonian Dynamics
  - resonance structures and effects
  - clues to solar system stability
  - development of fast and/or accurate numerical integration methods
    - mathematically interesting in and of themselves (mappings)

Fun Stuff: Mass determinations

- only ~12 masses currently known
- asteroid-asteroid perturbations
  - currently the most reliable method (~10-25%)
  - radar observations are best
  - USNO: Ceres, Pallas, Vesta, Eunomia
    - over 400 useful encounters in near future
- perturbations of Mars(!)
  - radar observations of both asteroid and Mars
  - 3 masses determined (Ceres, Pallas, Vesta)
  - ~30 within detectable range

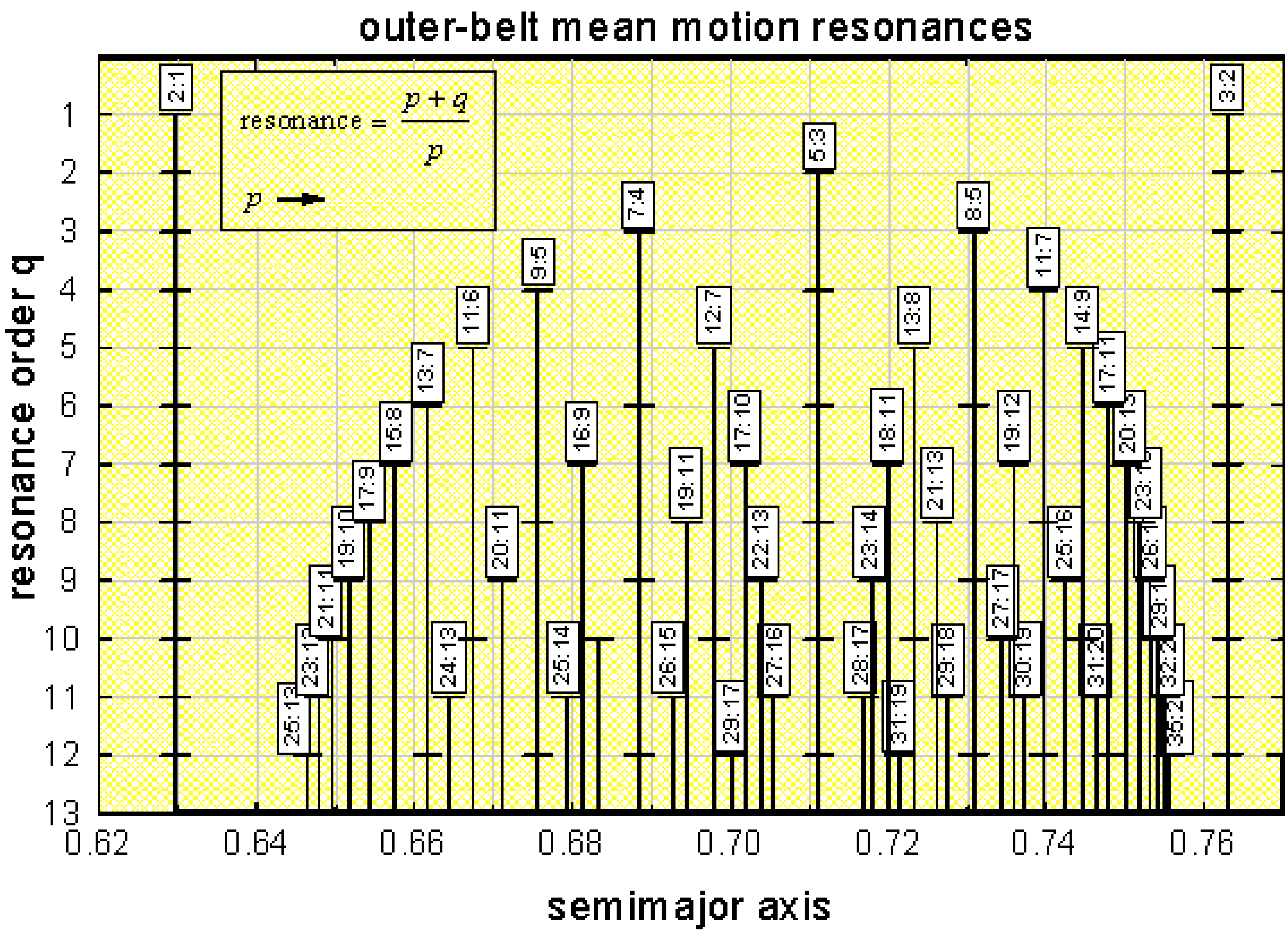
Fun Stuff: Mass determinations

- spacecraft perturbations
  - Galileo flew by too fast...
- asteroid satellites
  - $P^2 = \dfrac{4\pi^2}{G(M+m)} a^3$
  - Galileo flew by too fast...

Fun Stuff: Chaotic motion and resonances

- What are resonances?
  - mean motion resonances
  - secular resonances
- Mapping out the resonance structures
  - no stable regions between Jupiter and Saturn
  - chaotic zones correspond to the Kirkwood gaps!
  - excursions into high-eccentricity regions produce planet-crossing trajectories
    - reservoir of NEAs
    - reservoir of meteorites to inner solar system

Mean Motion Resonance Structure in the Outer Asteroid Belt



Chaotic Zones

- Chaotic zone structure of the 2:1 resonance

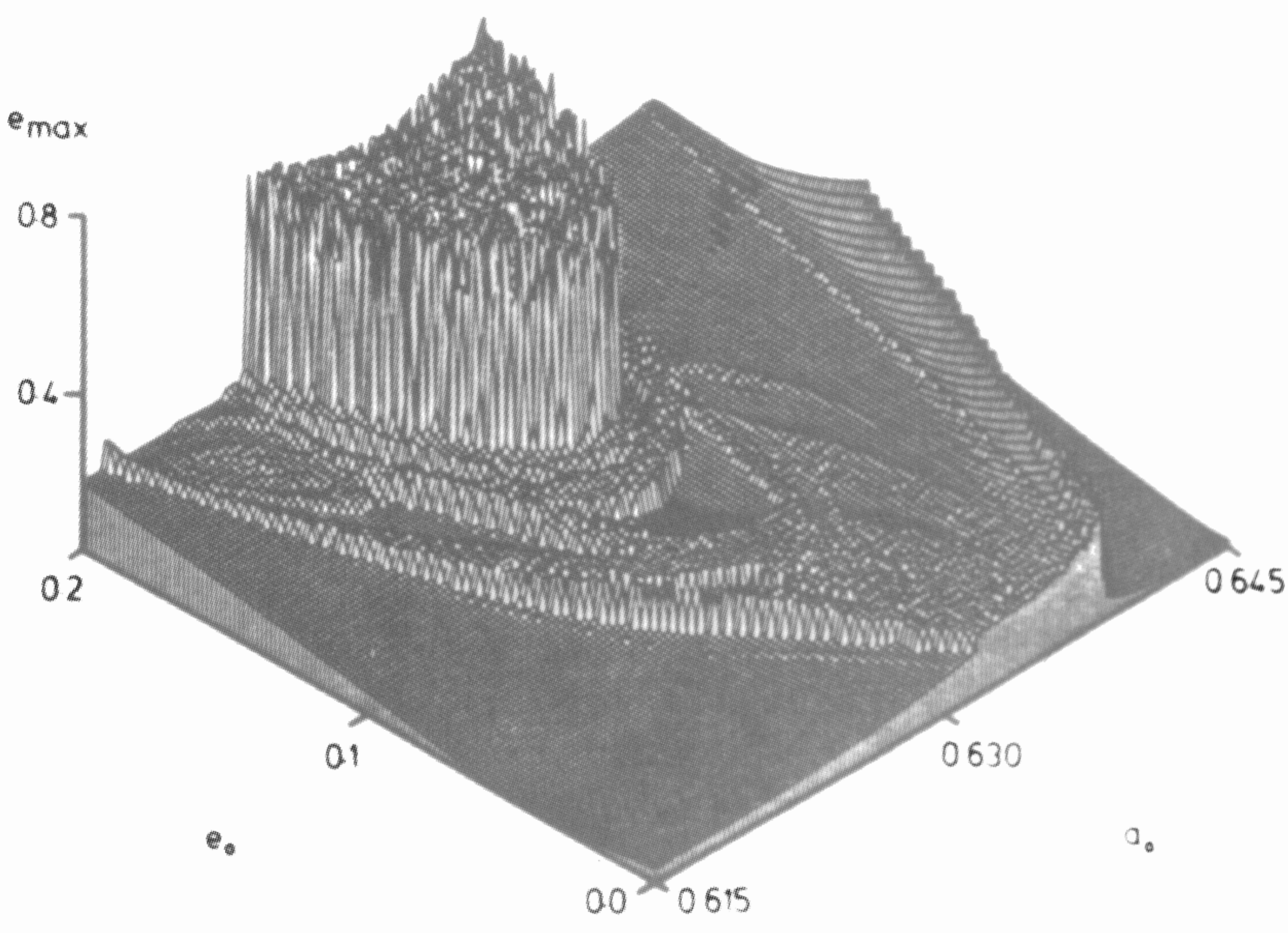
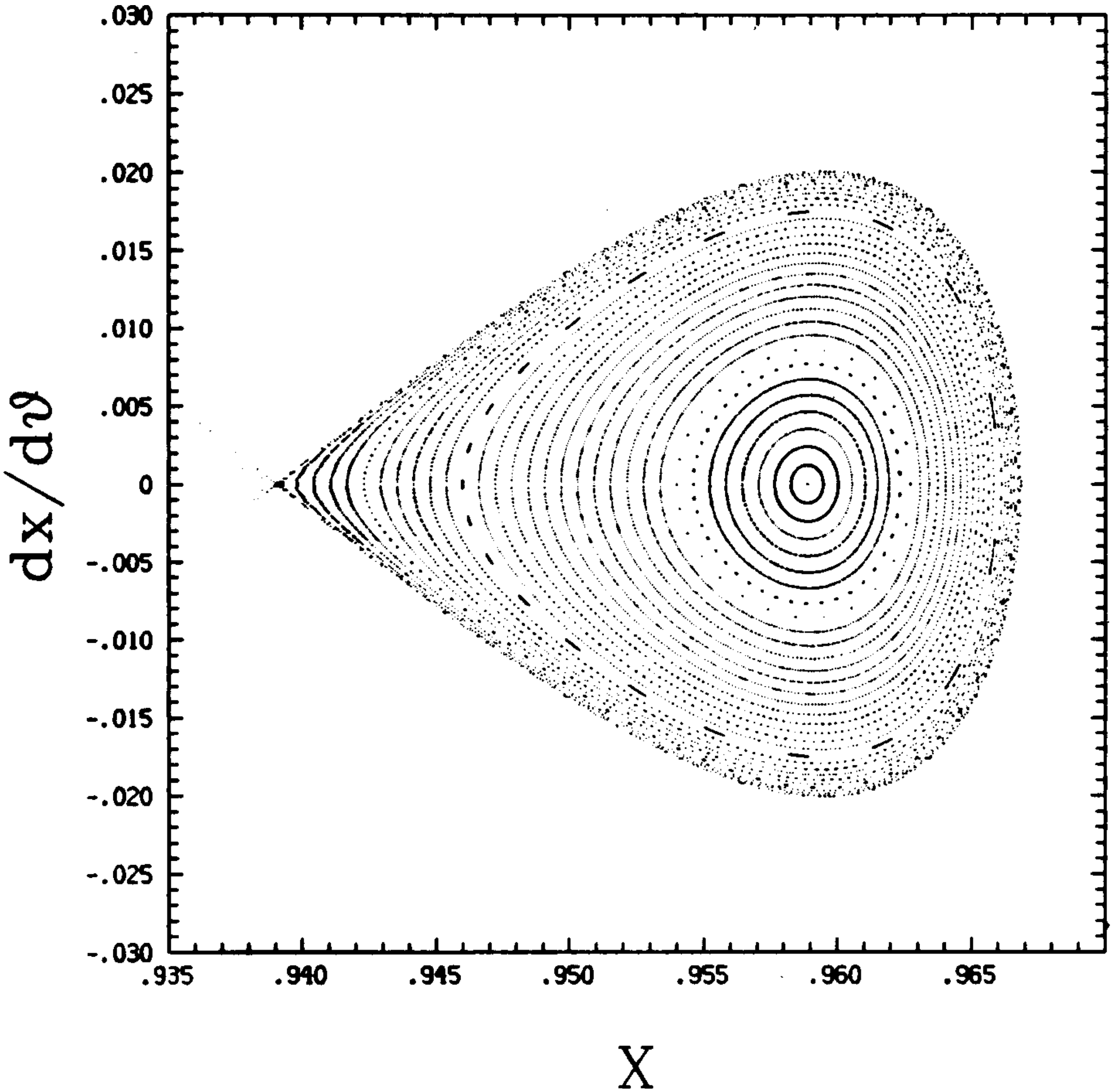


Fig. 2. Maximum eccentricity reached after 7000 Jupiter periods for test asteroids (figure from Murray 1986).

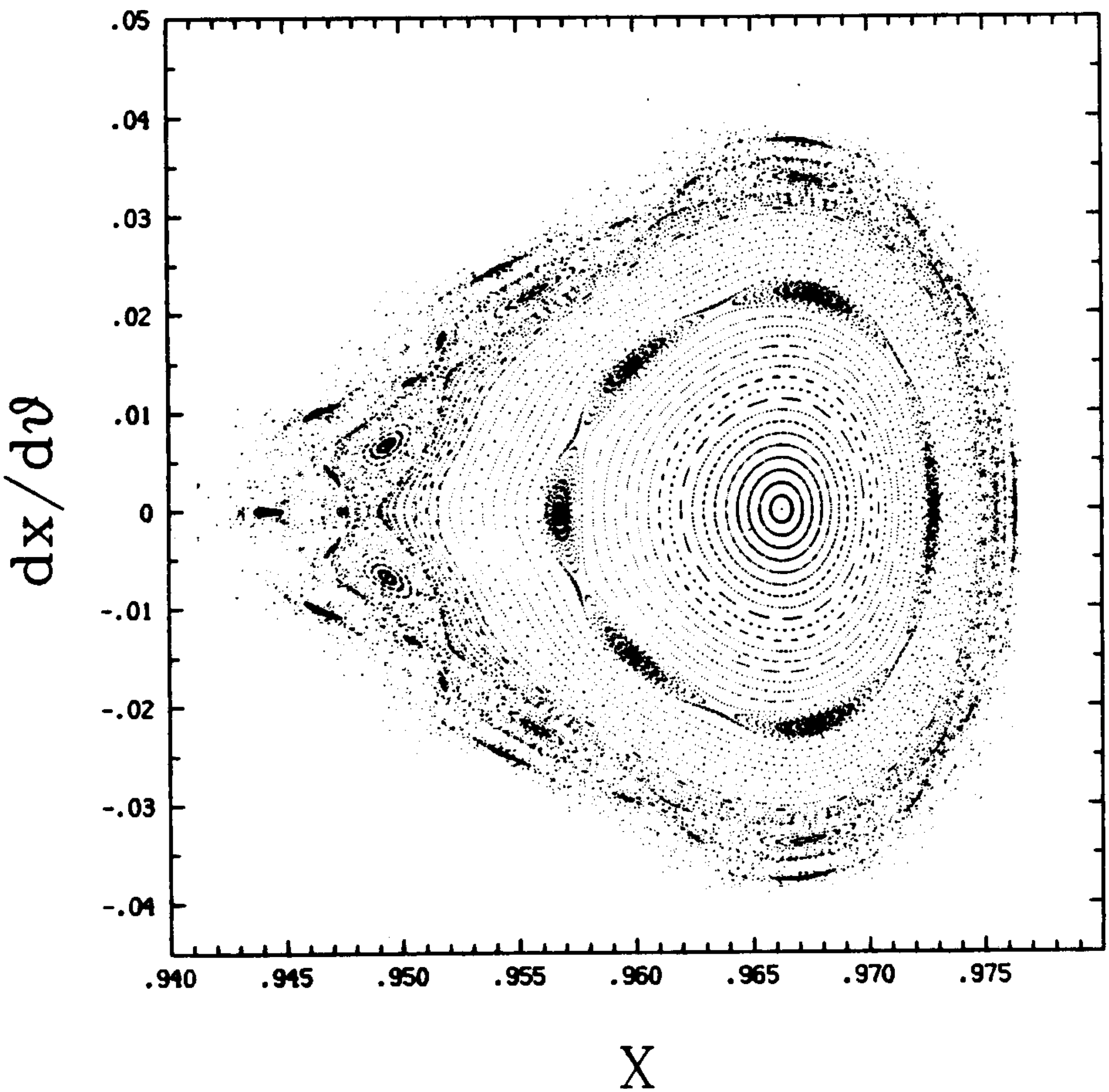
Surface of Section

- Regular motion



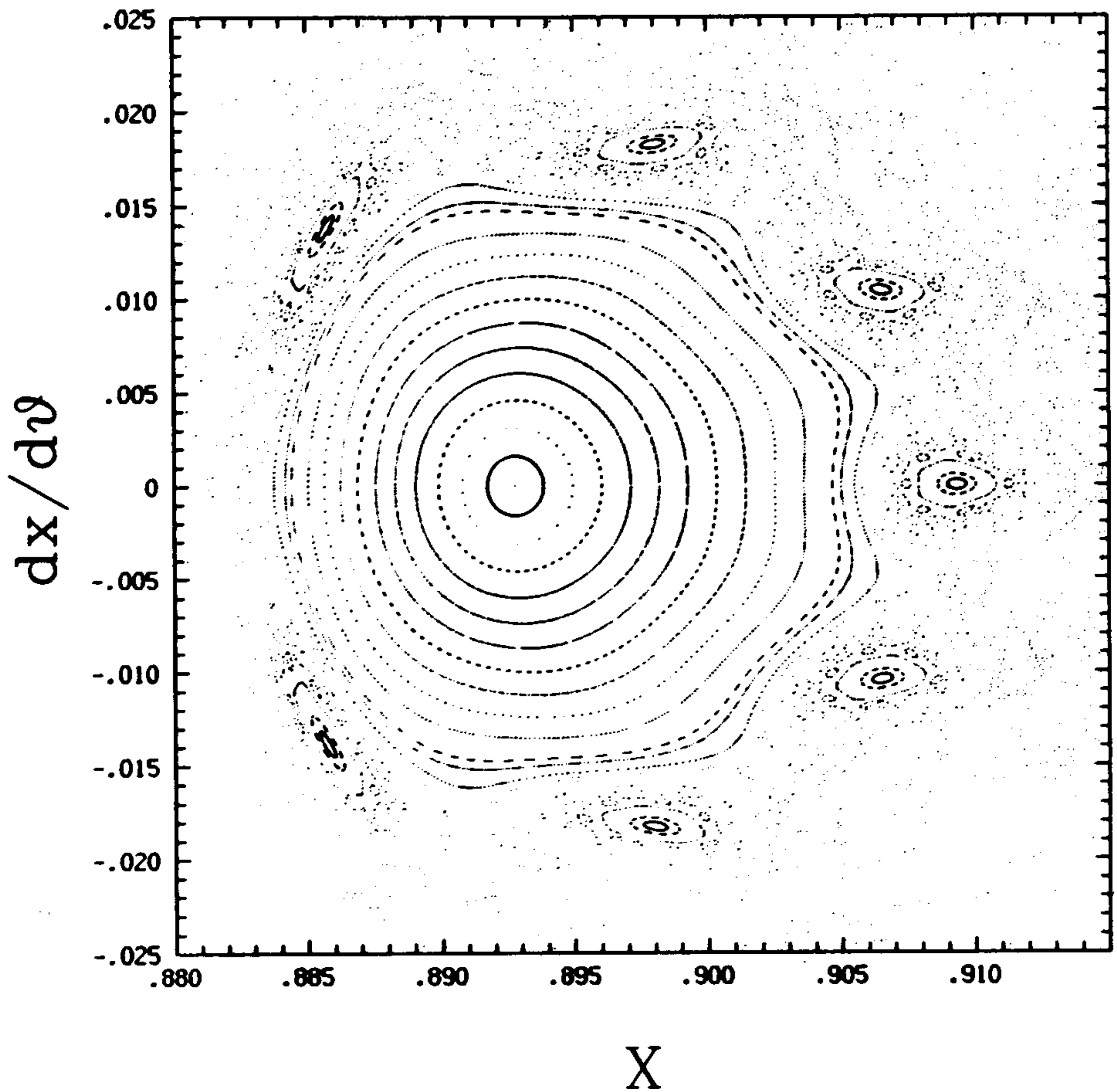
Surface of Section

- Chaotic motion



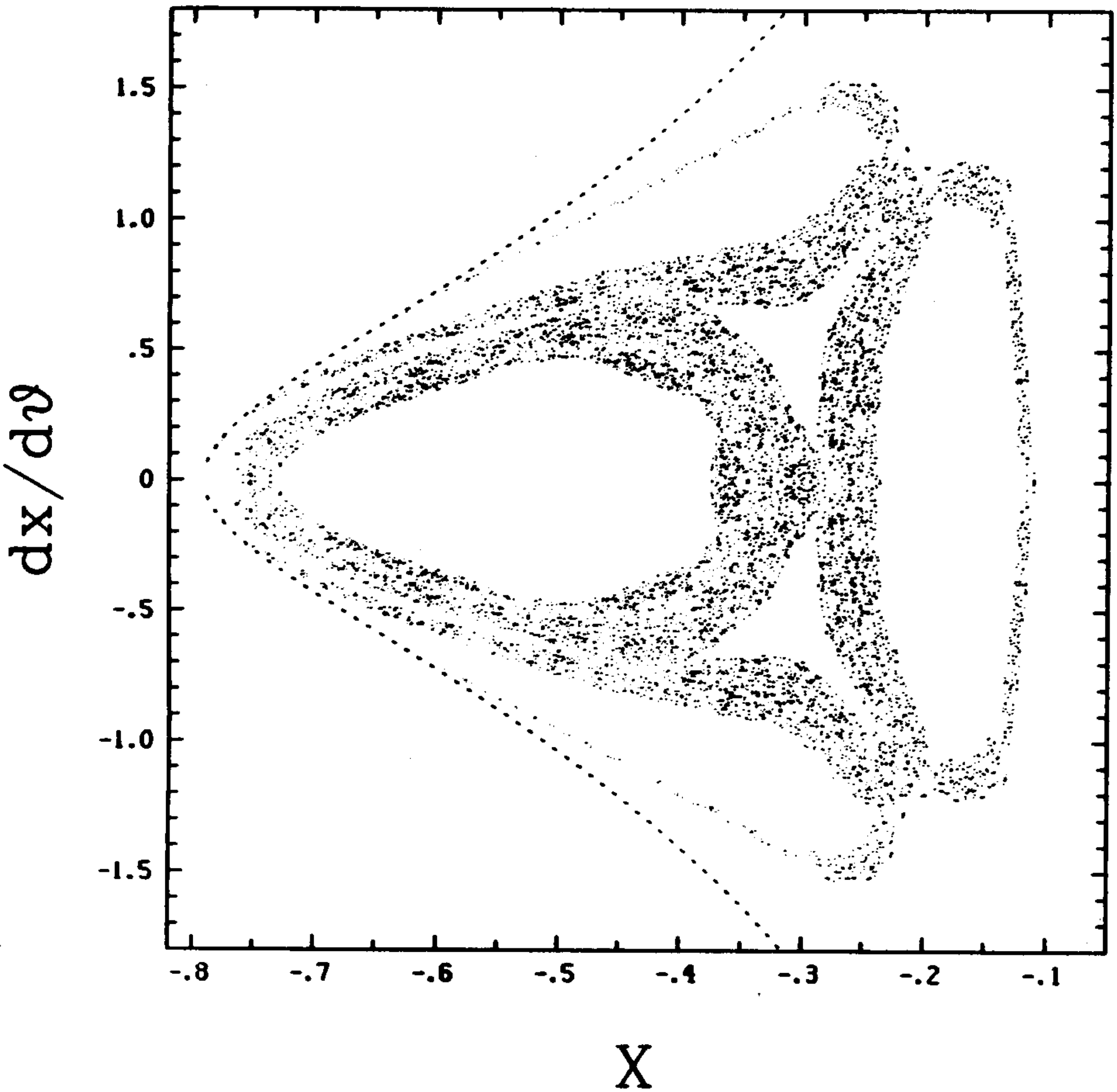
Surface of Section

- Strong chaos
- Resonant islands



Surface of Section

- Large excursions



Chaotic Regions

- Large excursions possible
  - planet-crossing trajectories

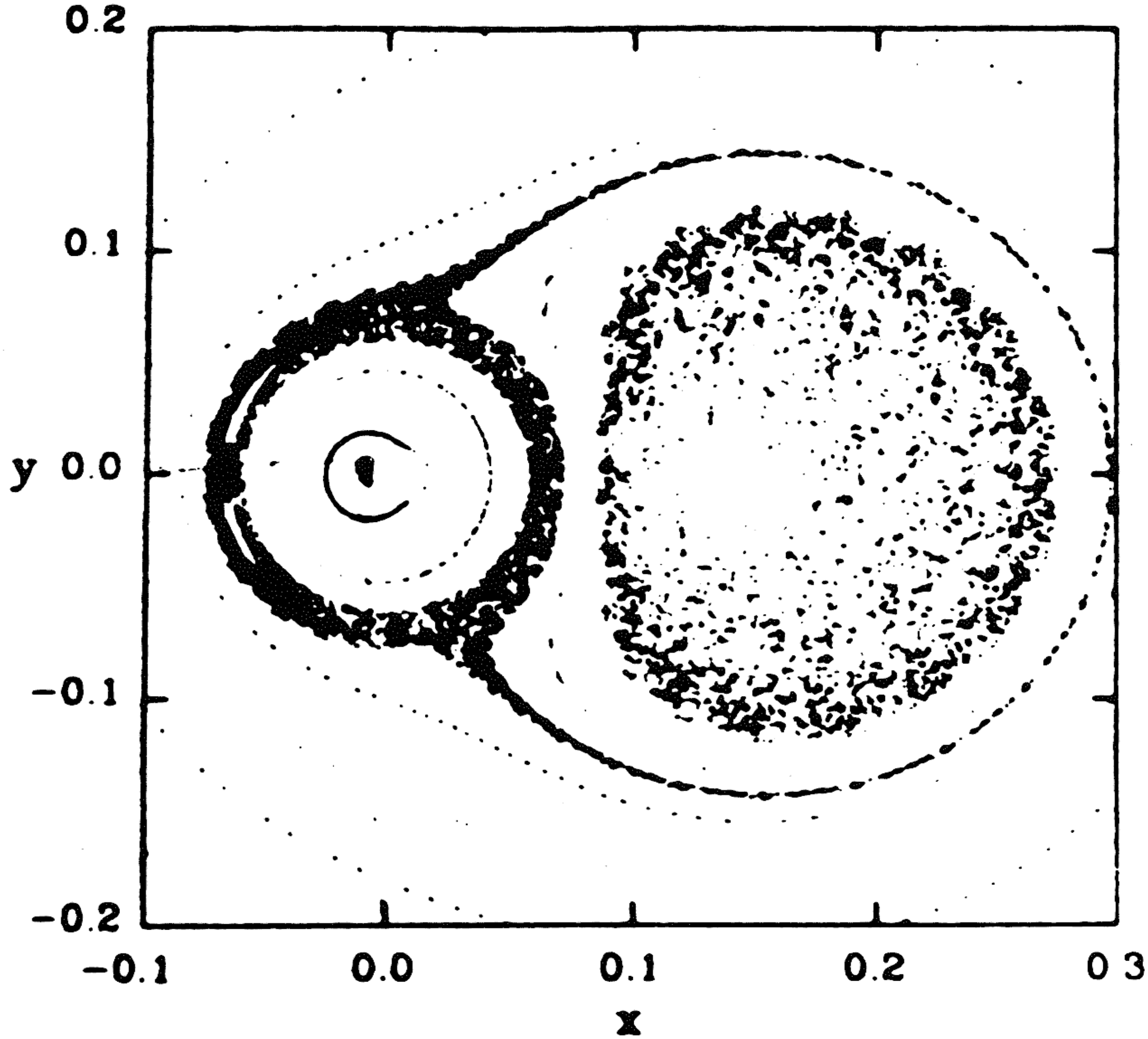


Fig. 3. Numerically generated surface of section computed with Wisdom's mapping. Large chaotic zones appear. The narrow region generates high eccentricities at irregular intervals (figure from Wisdom 1985).

Overlapping Resonances

- Resonance overlap produces regions of chaotic motion

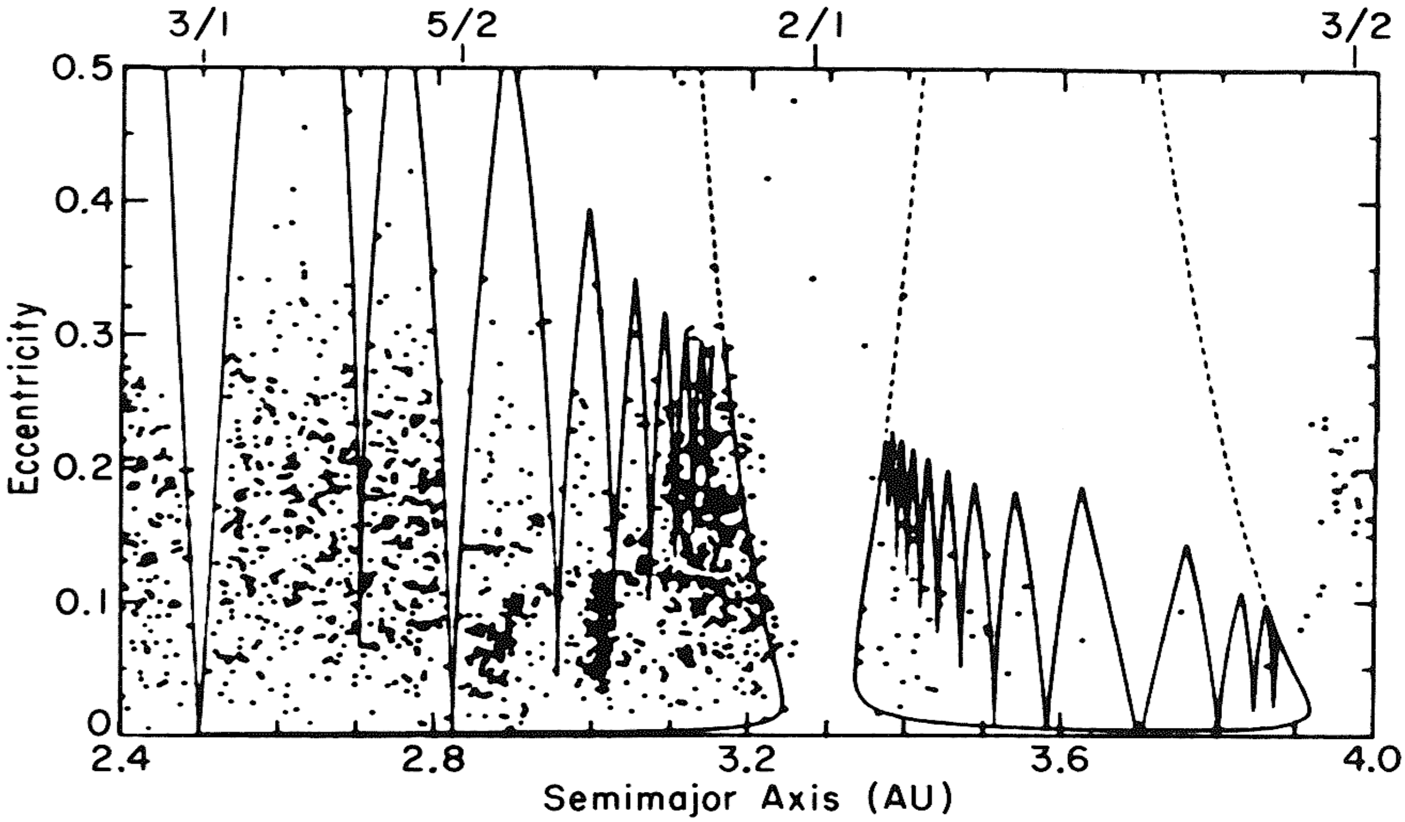
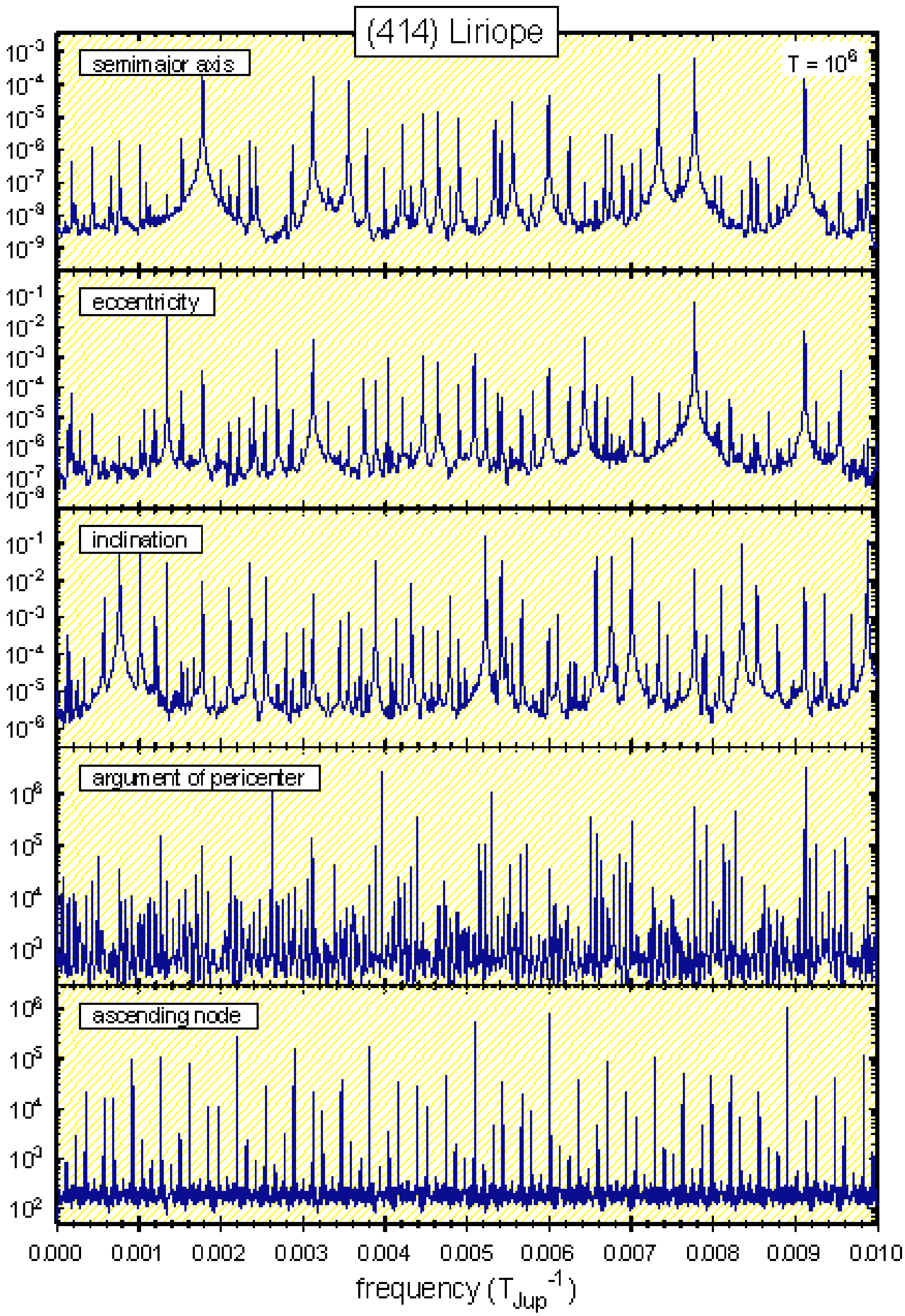


Fig. 3. All the numbered asteroids listed in the TRIAD file (Bender 1979) are plotted. The solid lines represent the libration width associated with the leading eccentricity term in the expansion of the perturbing function at the strongest Jovian resonances. Resonance overlap occurs where the solid lines meet. In the region of resonance overlap, the libration widths of the 2:1 and 3:2 resonances are represented by dashed lines (figure courtesy of Dermott and Murray 1983).

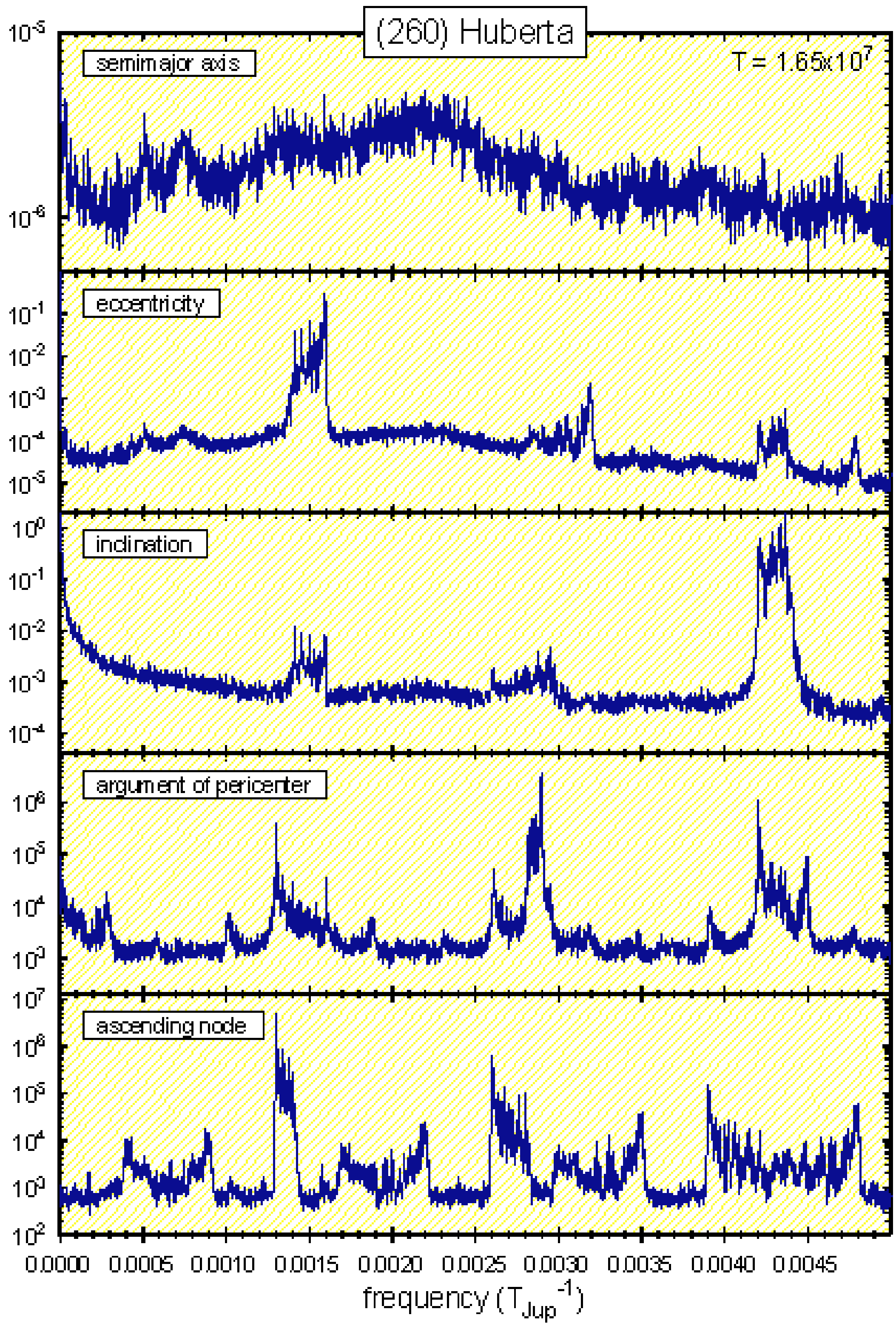
Fun Stuff: Measures of chaotic motion

- Power spectra of outer belt asteroids
  - extreme chaos

Power Spectrum of 414 Liriope



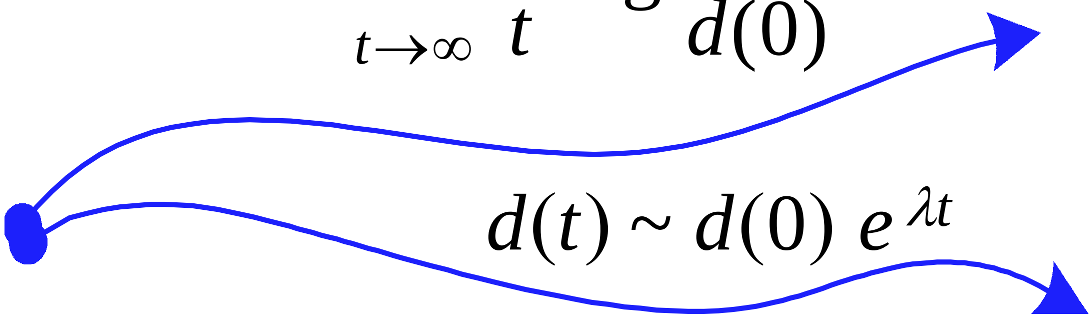
Power Spectrum of 260 Huberta



Fun Stuff: Measures of chaotic motion

- The Lyapunov exponent λ is a measure of orbit separation:

$$\lambda \equiv \lim_{t \to \infty} \frac{1}{t} \log \frac{d(t)}{d(0)}$$



where d(t) is distance in phase space.

- $\lambda > 0$ indicates chaos

- Magnitude of λ is a measure of severity of chaotic motion.

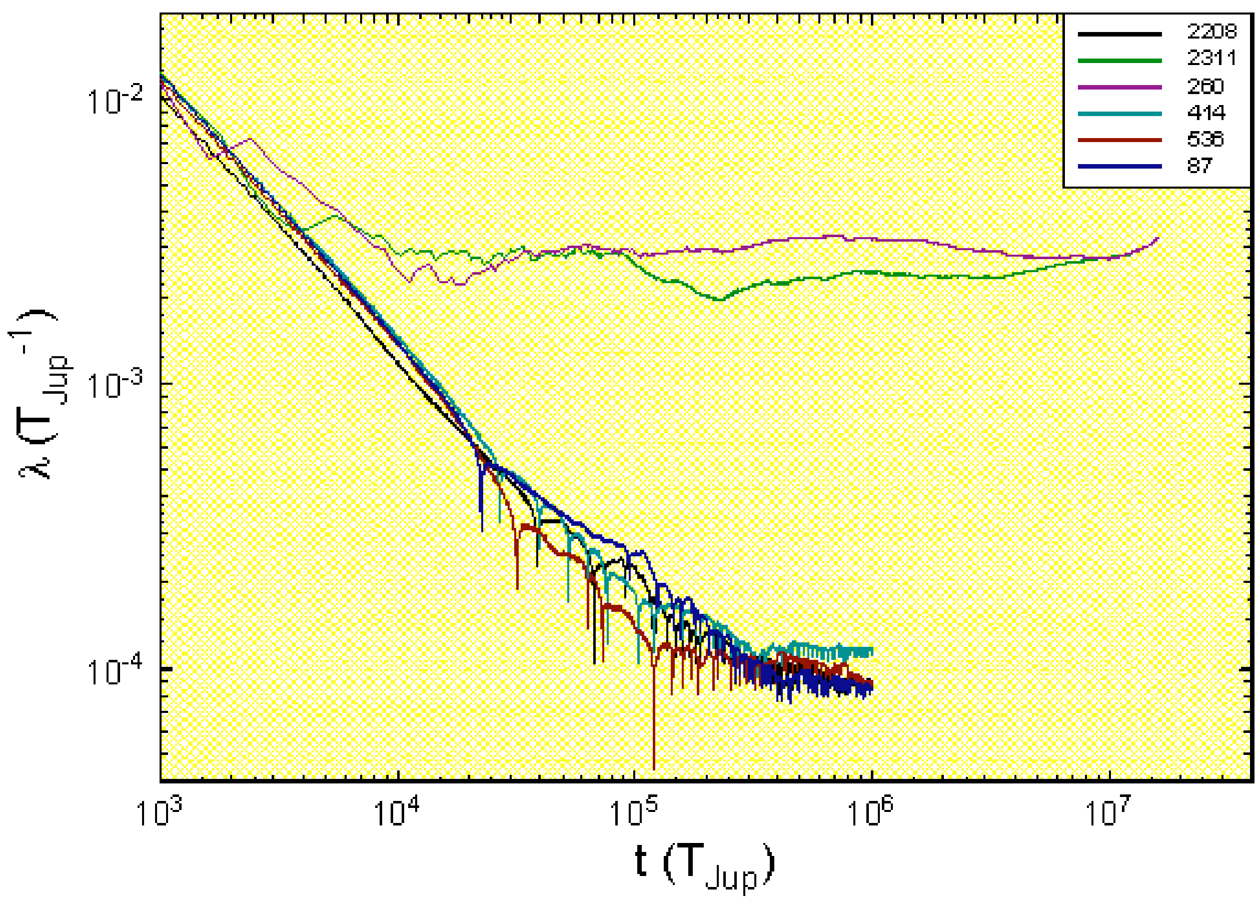
- **Question**: how can we relate a "Lyapunov timescale"

$$T_L \equiv \frac{1}{\lambda}$$

to a dynamical stability timescale?

Lyapunov Exponent Examples

- Typical behavior of the Lyapunov exponent over time for chaotic orbits:



Here we have $\lambda(t)$ for 6 outer belt asteroids. All exhibit strong chaotic motion, while two are extremely chaotic.

Lyapunov Exponent Relation

- The *Lyapunov exponent relation* is an empirically determined one:

$$\log \frac{T_e}{T_0} = a + b \log \frac{T_L}{T_0}$$

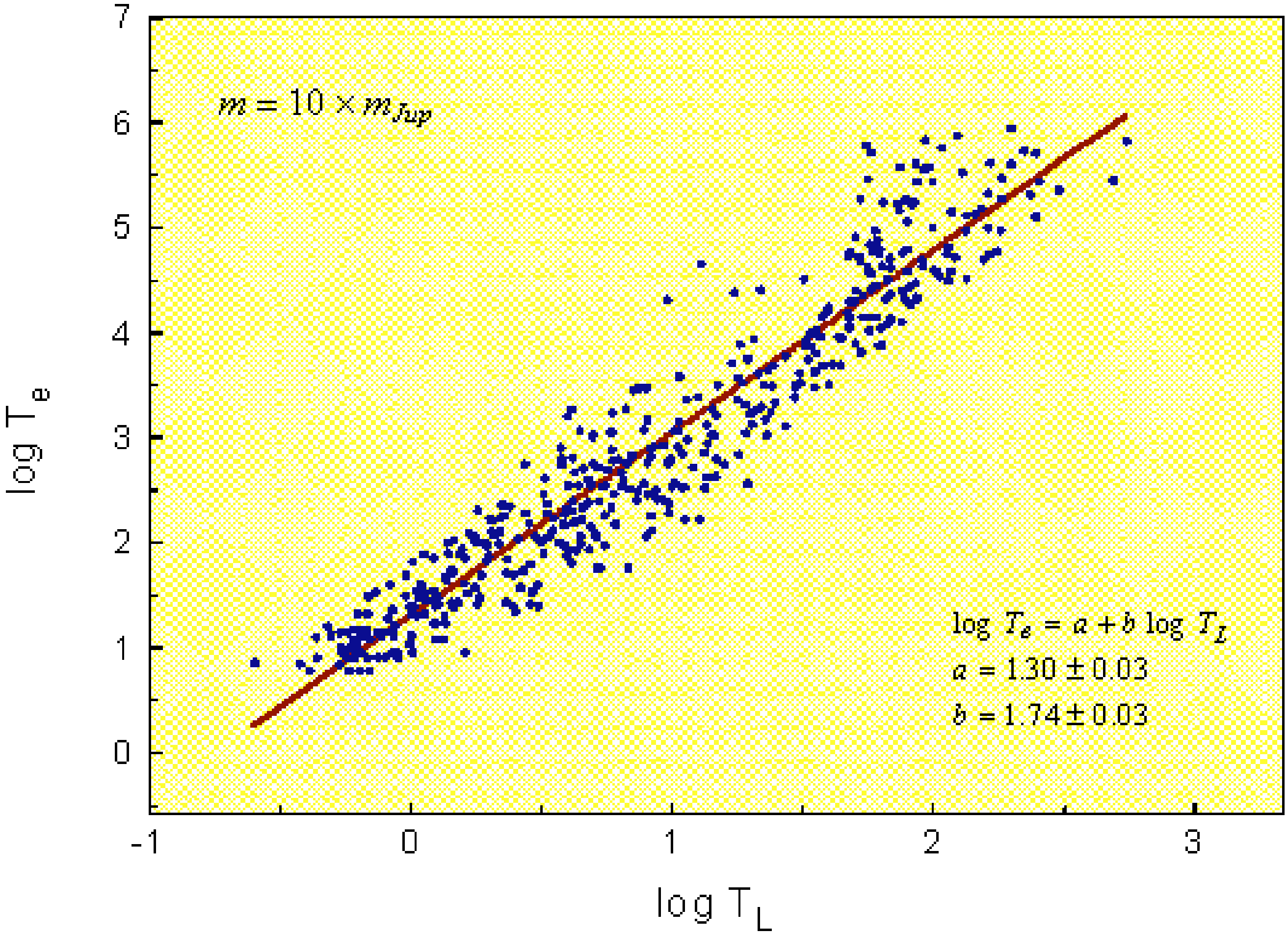
  where T_e is the "event" timescale (time to orbit crossing, collision, or ejection) and a, b, and T_0 are constants.

- For a large variety of dynamical systems,

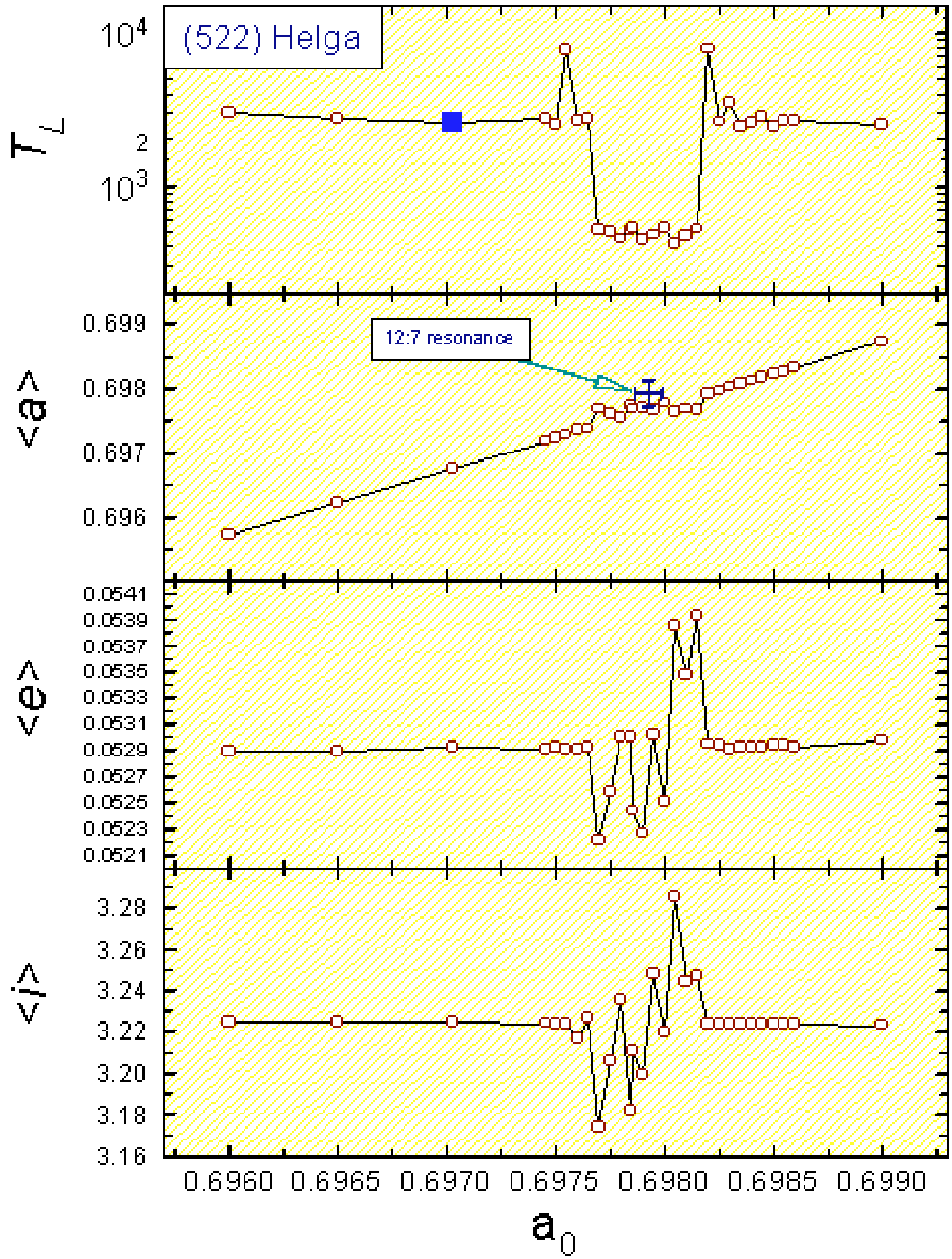
$$0.4 \le a \le 2 \quad \text{and} \quad 1.4 \le b \le 1.9$$

- Integrating a dynamical system (e.g. the solar system) to T_e is normally very expensive, while integrating just to determine T_L is not (by ~3-5 orders of magnitude). Hence the relation is potentially a powerful prediction mechanism.

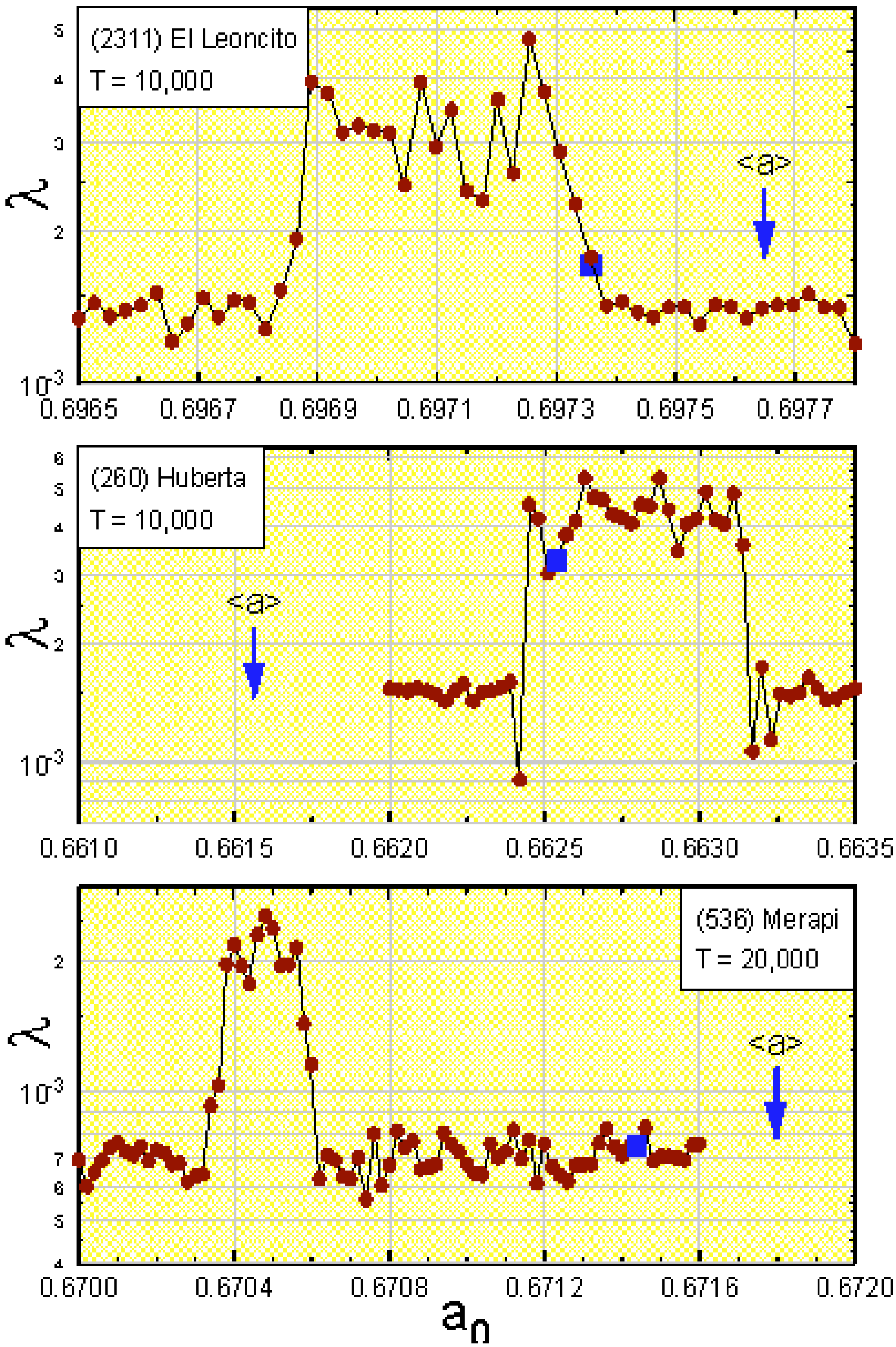
Lyapunov Exponent Relation



Variation across High-Order Resonance



Variation across Resonances



Variation across Resonances

- These 2 panels are a scan of λ across initial semimajor axis in a small section of the outer asteroid belt (but larger than the snippets in the previous panels). The detected resonances are marked. Note the change of ordinate scale in the upper panel.